EFFECT OF INSULATOR APPLICATION ON THE LEAKAGE CURRENT PERFORMANCE OF WOODPOLE DISTRIBUTION LINE STRUCTURES

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A research report submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg, in partial fulfilment of the requirements for the degree of Master of Science in Engineering.

Johannesburg, 29 February 2016

DECLARATION

I declare that this research report is my own unaided work except where otherwise acknowledged. The work was accomplished while employed by Eskom Holdings SOC Ltd, Research, Testing and Development and studying part-time at the University of the Witwatersrand, Johannesburg. It is being submitted for the Degree of Master of Science to the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination.

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ABSTRACT

Medium voltage distribution networks use woodpole structures extensively. Woodpole structures are susceptible to burning, referred to as pole-top fires which can result in a loss of supply and electrocution hazard to the public and animals in the area. Leakage current flowing inside or on the surface of the wood is the cause of pole-top fires. Leakage current measurements on woodpole structures were conducted for varying insulator material, insulator shape and positioning on the cross-arm. This comprised laboratory measurements on a reduced scale woodpole structure that was artificially polluted to obtain a baseline. To substantiate the results, measurements on full scale woodpole structures exposed to natural pollution are presented. Leakage current performance of a woodpole structure was found to be most impacted by the choice of insulator material followed by insulator profile for silicone rubber insulators and insulator orientation for porcelain insulators. Structures with silicone rubber insulators recorded low leakage current magnitudes. The structure with Room Temperature Vulcanized (RTV) silicone rubber coated insulators yielded the most improved structure leakage current performance provided hydrophobicity is retained. The structure insulators require reapplication of the silicone rubber coating after a certain period in service. Therefore, the use of High Temperature Vulcanised (HTV) silicone rubber insulators with a wide and short profile and alternating sheds was identified to be the most attractive solution for reducing the risk of pole-top fires occurring. For cases when only porcelain insulators can be used, mounting the insulators horizontally results in less leakage current flow on the structure compared to mounting the insulators vertically. The classic woodpole distribution structure has a combination of unfavourable insulator material and orientation, close proximity to sources of pollution and critical wetting can therefore lead to severe burning at the insulation coordination gap during light pollution as shown from visual inspections. The evaluated structure cases all exhibited a voltage at the insulation coordination gap implying an existing risk of burning at the gap. Suggestions for insulator application for improved structure leakage current performance to reduce the risk of pole-top fires are offered.

This work is dedicated to God for his protection, grace and mercy

ACKNOWLEDGEMENTS

The following people are hereby acknowledged and thanked for their contribution and support:

- My husband, Oageng, my daughter Oresiametse and my entire family for their patience, support and endless encouragement.
- My mentor, Dr Andreas Beutel, for creating a learning environment and career growing opportunity that enabled me to complete this work, for his advice and help with tests at the Corona Cage and at Koeberg Insulator Pollution Test Station.
- My supervisor, Dr John Van Coller, for his guidance while completing the work.
- Mikhuva Ntshani for his help during all the tests, contribution in compiling the laboratory safe working procedure and his project management on pole-top fires project that facilitated Eskom's funding for all the tests conducted.
- All co-authors for their perusal of published ISH 2013 and ISH 2015 papers pertaining to this work.
- Koeberg Insulator Pollution Test Station staff: David Mvayo, Rob Watson, Raphael Swinny for their help with the testing.
- The Eskom Research, Testing and Development staff, Elvis Mathebula, Nishanth Parus, Matimba Mathebula, Abongile Mangxola and Arnold Msimanga for their helping hand during testing at Corona Cage.
- Eskom's pole-top fires working group, for giving direction during the research.
- Mace Technology for coating porcelain post insulators with room temperature vulcanized silicone rubber.

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1 INTRODUCTION

For power to be distributed to end users in a safe, reliable and economic manner, Medium Voltage (MV) electric power at tens of kilovolts is distributed in a network to the end user. South African power utility Eskom has approximately 325 000 km of distribution lines in their infrastructure. 22 kV overhead lines are common, though other lines with voltage levels between 11 kV and 88 kV also exist [1]. Due to the good insulating properties of wood and relatively low costs, the network construction is primarily overhead lines comprising woodpoles and in many cases wooden cross-arms. Other structures use concrete poles or woodpoles with steel cross-arms [1].

Distribution woodpole structures are susceptible to burning caused by leakage currents [2-9]. The phenomenon is known as pole-top fires. Pole-top fires are problematic because they can result in a loss of supply, bush fires and damage to farms and property. Moreover, pole-top fires can cause live conductors to hang low. Live conductors that hang close to the ground pose an electrocution danger that can lead to injury or death to members of the public and animals in the area since the power utility has no means of detecting low-hanging conductors [1, 4].

This research report evaluates the effect of insulator application on the leakage current performance of woodpole distribution line structures. Structure elements that contribute to the leakage current performance of a woodpole structure are phase insulators and the type of bonding and earthing utilised. Hence the application and choice of phase insulators are of particular interest. These are investigated together with a partial bonding arrangement on the woodpole structure.

1.1 Mechanism of Pole-Top Fires

The mechanism of pole-top fires has been explained in the 1940’s by Ross in [2] and concurs with recent explanations in [3-9].

The mechanism is initiated during a prolonged season of little or no rain in which substantial collection of pollution on phase insulators and drying of the woodpole occurs. At the end of the season or change of seasons, parts of the woodpole and pollution on the surface of phase insulators can be slightly wetted from light rain, high humidity, mist, fog or dew. The slightly moistened pollution will therefore become electrically conductive and result in the flow of leakage current which can find a path from the phase insulators’ surface through the inside of the woodpole and/or onto the surface of the woodpole. In other instances accumulation of conductive pollution from sea spray may lead to leakage current flow without the presences of the wetting agents previously mentioned.

Under certain climatic conditions (high humidity and temperature accompanied by a breeze) leakage current will cause dry band arcing on the surface of the woodpole and, if sustained for a lengthy period, may lead to smouldering of the woodpole and ultimately burning of the woodpole. In addition fires can start from the inside of the woodpole due to high electric fields that exist between the energized metal fittings and the dry parts of the woodpole [2, 5]. The high voltage gradient leads to confined discharges that, if they continue for an extended period, will result in burning of the woodpole [2, 5].

1.2 Typical Distribution Woodpole Structure

Figure 1.1 shows a typical three-phase woodpole distribution line structure [1]. The structure is an intermediate type with a substantially horizontal configuration, which is typical on most distribution lines [3].

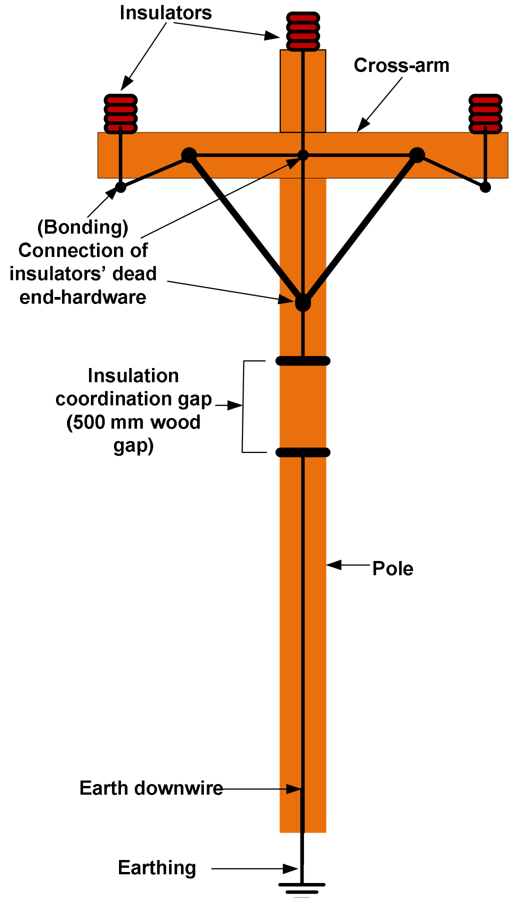


Figure 1.1: Common distribution woodpole structure [3 p.2]

1.2.1 Insulators

Insulators are used for the safe mounting of live conductors on a distribution line structure. For the purposes of the present work, the insulators will be mounted on a cross-arm. Insulators on 22 kV (line-to-line) distribution lines operated by Eskom are required to have a lightning impulse withstand level of 170 kV. The types of insulators used on woodpole distribution lines may be post or pin type porcelain or silicone rubber insulators and suspension type long rod silicone rubber insulators as shown in Figure 1.2. Post insulators are designed to be firmly mounted on a structure for support of the conductor. Pin insulators consist of a disc with a pin through it and can be connected to form a long insulator string. Long rod insulators are typically thin and long compared to other types of insulators and are used to suspend the conductor. Porcelain is a ceramic that has been glazed to make it smooth. Silicone rubber is a polymer with fillings and additives to make a rubber like material that normally surrounds a fibreglass core. More details regarding types of insulators, insulator material and application are found in references [10-12]. Looking at pole-top fires, capped insulators (insulators with a metal base fitting) are recommended to ensure complete electrical bonding of the structure and elimination of pole-top fires on the woodpole cross-arm as stated by Beutel in [7].

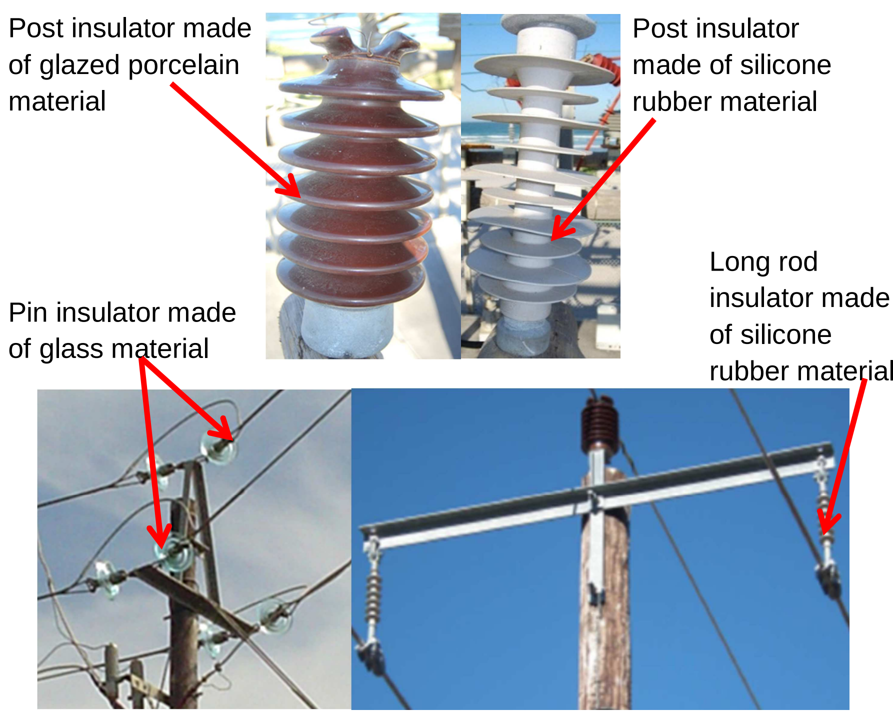


Figure 1.2: Types of insulators used on a distribution line

1.2.2 Cross-arm

Figure 1.3 illustrates the configuration for woodpole and steel frame cross-arms. Woodpole structures can be built with a wood or steel T-frame cross-arm using a horizontal configuration. An A-frame steel cross-arm is used to obtain a delta configuration which can have all insulators mounted vertically or have the outer phase insulators mounted horizontally. Two woodpole cross-arms can also be used for the delta configuration. The use of a steel cross-arm eliminates pole-top fires occurring on the cross-arm, but does not on its own eliminate burning of the woodpole.

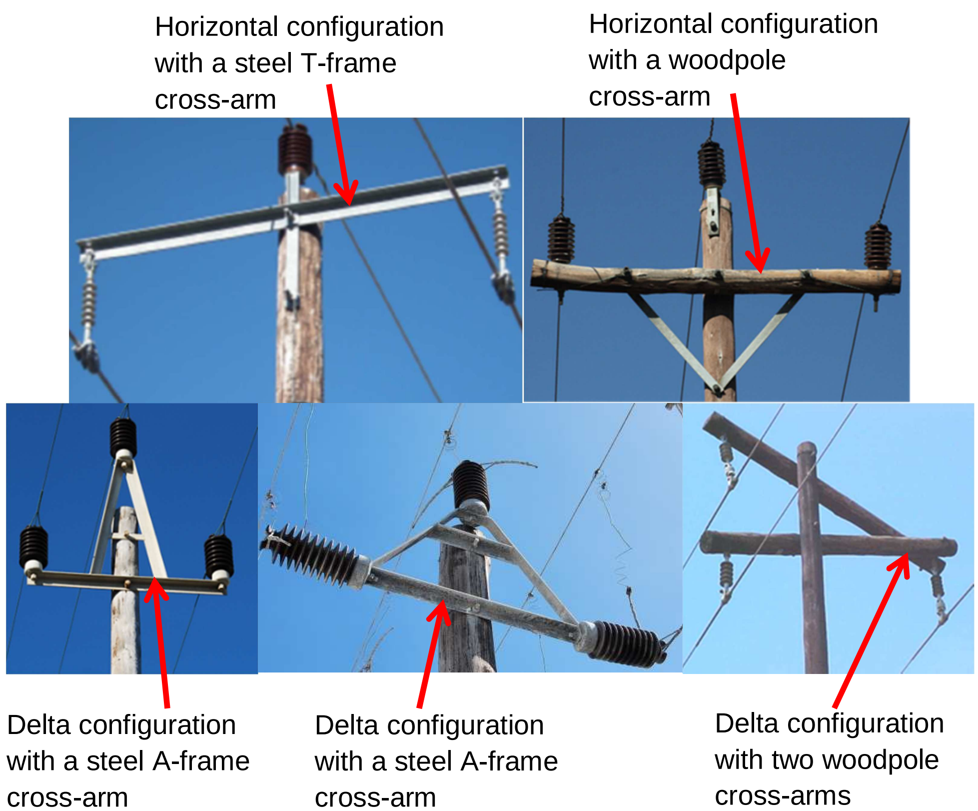


Figure 1.3: Types of configurations used for distribution structures

1.2.3 Bonding and earthing

The bonding and earthing practice shown in Figure 1.1 makes the structure partially bonded and earthed, since the metal hardware on the pole-top is bonded together electrically and earthed through a 500 mm insulation coordination gap on the vertical pole. The purpose of this gap is to improve the structure's lightning withstand capabilities by increasing its Basic Insulation Level (BIL) by 150 kV phase-to-earth to 300 kV [1]. Pole-top fires may occur in the insulation coordination gap since leakage current must cross this gap, internally and/or on the surface of the wood, to get to earth. Full bonding and earthing, where the insulation coordination gap is removed and the earth downwire is continuous, substantially eliminates pole-top fires if bonding and earthing is done correctly [6]. However, the structure will be left susceptible to tripping due to overvoltages caused by induced lightning surges. Moreover, the implications for human and bird safety on such a structure require further evaluation.

1.3 Premise

The premise is that insulators can be selected and applied to achieve reduced leakage current magnitude on a woodpole structure because pollution accumulation on an insulator surface changes depending on insulator material, form or shape. Likewise, leakage current performance of an insulator is impacted by the position that the insulator is mounted in relation to pollution, wind and rain [10] and likewise the leakage current performance of the whole structure.

It is well-known that the ability (or lack thereof) of an insulator material to repel water and limit pollution accumulation has a direct influence on the insulator's surface resistivity, see Figure 1.4 illustrating a typical circuit representation of an insulator. Consequently the magnitude of leakage current varies with the insulator's surface resistivity. The conductivity formula in Equation 1.1 from [11 p.24] shows that insulator shape influences the conductivity of the surface and ultimately impacts on the insulator's surface resistivity and its leakage current performance [10-11]. It is possible for insulator orientation to have similar effect because pollution accumulates and washes off differently on an insulator that is mounted vertically compared to the one that is horizontally installed.

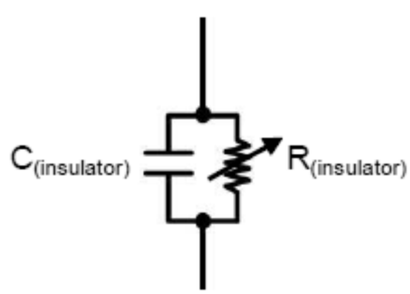


Figure 1.4: Typical and simplified representation of an insulator

$$R_{pol} = F/\sigma_s$$ **(1.1) [11 p.24]**

where

R_{pol}: Surface layer resistance of electrolytic pollution layer (MΩ)

F: Form factor of the insulator

σ_s: Surface conductivity of electrolytic pollution layer (µS)

Studies have previously been undertaken to investigate leakage current performance of individual insulators [12]. Individual insulator performance is traditionally determined by measuring the leakage current through the insulator pollution layer where measurement is performed at the base of the insulator.

Ross stated that the “insulator surface resistance in addition with the total woodpole resistance forming a series circuit determines the magnitude of leakage current flowing through or on the structure” [2 p.280]. The research reported in this document investigates the effect of insulator properties on the leakage current performance of a complete three phase Medium Voltage (MV) distribution woodpole structure with phase insulators, partial bonding and related hardware. It entails measuring the leakage current along the earth downwire (below the insulation coordination gap) of the MV distribution woodpole structure.

Reducing the risk of pole-top fires utilising only insulator choice and application on a partially bonded structure is investigated.

1.4 Research Questions

The research questions to be answered are:

1. What is the effect of insulator orientation on the leakage current (along the earth downwire) of a MV woodpole distribution structure?

2. What is the effect of insulator material on the leakage current (along the earth downwire) of a MV woodpole distribution structure?

3. What is the effect of insulator profile on the leakage current (along the earth downwire) of a MV woodpole distribution structure?

These are answered by analysing results from laboratory measurements on reduced scale woodpole structure and long term measurements on full scale woodpole structures exposed to natural pollution.

Thereafter results were consolidated to evaluate the effect of insulator orientation, insulator material or insulator profile according to the earth downwire leakage current magnitude and answer the research question “can the magnitude of leakage current be reduced from improved application of insulator orientation, insulator material and insulator profile on a woodpole distribution structure”?

1.5 Research Report Outline

The report comprises five sections in addition to this section as described below.

Section 2 is a review and summary of previous research on pole-top fires. The literature review also includes leakage current performance of individually tested insulators.

Section 3 has details of reduced scale laboratory test measurements performed on an artificially polluted woodpole distribution structure for different cases of insulator types and arrangements.

Section 4 presents full scale long term test measurements conducted on selected woodpole distribution structures exposed to natural pollution at a coastal test facility.

Section 5 reviews the outcomes of the literature survey and tests and analyses these to answer the research questions.

Concluding remarks and suggestions for further work are provided in Section 6.

2 REVIEW OF PREVIOUS POLE-TOP FIRE INVESTIGATIONS AND INSULATOR LEAKAGE CURRENT INVESTIGATIONS

The purpose of this section is to review available literature regarding pole-top fires and leakage current performance of individually tested insulators. The outcomes are used as guidance for expectations from the results of the tests reported on later in this document.

2.1 Pole-Top Fires

The occurrence of pole-top fires has been documented since the 1940's. They have been experienced in South Africa, Kenya, Australia, USA and the Middle East [2-9, 13-15]. Fires on woodpole structures can occur due to lightning, bush fires, a detached live conductor making contact with the wood pole or cross-arm or sustained leakage current from polluted phase insulators. The last cause of woodpole structure burning leads to what is known as pole-top fires. It is known as such because these fires occur predominately on the top of the structure on the wood cross-arm or pole. Pole-top fires occur because the three conditions for combustion which are heat, fuel and oxygen are met by the flow of leakage current which provides heat, fuel from the structure wood and the ambient air, which may be supported by wind that supplies oxygen.

2.1.1 South African knowledge

Persadh [5]

Persadh's work in [5] contributed greatly towards the knowledge on pole-top fires in a South African context. He provided statistical information on the prevalence of pole-top fires in South Africa, the analysis of existing structure designs and their vulnerability to pole-top fires. Furthermore, Eskom's internal pole-top fires research by Loxton was presented in detail.

Pole-top fires were reported to occur mostly in Kwa-Zulu Natal (KZN) because of conditions comprising high levels of pollution from sugar cane burning by the farmers, industrial and marine pollution and high relative humidity and temperature synonymous with northern coast weather patterns.

Persadh determined that unbonded or incompletely bonded structures with uncapped porcelain insulators resulted in the most pole-top fires. He proved and recommended the use of matched creepage distance porcelain insulators with metal base fitting together with "complete" structure bonding to mitigate pole-top fires. Capped porcelain insulators shown in Figure 2.1 have a conductive connection between the insulator base and the metal spindle attaching the insulator to the cross-arm and the bonding wire. Therefore a low resistance conductive path is provided for leakage current from the surface of the insulator onto the bonding. Details regarding insulator terms and parameters used in the report are found in Appendix A, reference [10] and [11]. Pole-top fires occurring at the cross-arm are therefore mitigated by prevented leakage current from flowing inside the woodpole cross-arm or on its surface. Further work in this regard was reported by Beutel et al in [7].

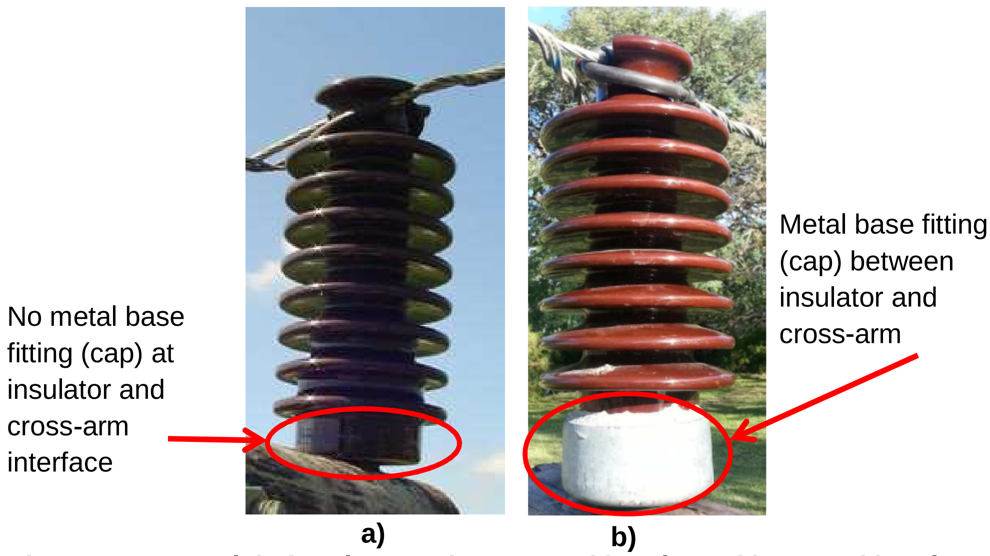


Figure 2.1: Porcelain insulators, a) uncapped insulator, b) capped insulator

Work by Eskom researcher Loxton reported in the dissertation showed that sustained currents of approximately 1 mA are capable of initiating pole-top fires. It is a lower level than that obtained by other researchers [6, 9].

It was stated that heavy pollution is not necessarily the determining factor when it comes to initiating pole-top fires. Other factors such as high wetness and high temperature are equally important. This was demonstrated with ESDD measurements that classified pollution in the Mtubatuba area as light even though a significant number of pole-top fires occurred. Loxton's investigation into woodpole resistivity showed that an increase in moisture level of wood reduces the resistance of the wood. The decrease is from mega-ohms to kilo-ohms when comparing a completely dry pole and a medium or heavily wetted pole. The decrease in resistance of the wood due to moisture content is typical and demonstrates the vulnerability of wet woodpoles to pole-top fires initiated from within the pole. He proposed mitigation methods such as applying conductive paint or silicone coating on the cross-arm and securing a metal strip around the cross-arm and attaching it from the insulator end fitting terminated 200 mm away. However, these methods do not prevent pole-top fires because a conductive path of low resistance is not provided and hence leakage current is able to flow into or onto the wood and initiate pole-top fires at the location where that occurs.

Thejane et al [4]

Thejane et al in [4] performed a review of pole-top fires work up to year 2012. The work involved summarising information related to South African and Australian pole-top fires experiences.

Outcomes from the summary regarding South African experience were that most pole-top fires occur at the insulation coordination gap of a partially bonded and earthed structure, in contrast to incidents on unbonded structures where most of the fires occurred on the cross-arm. In addition, structures that are not bonded or those that are incorrectly bonded are most likely to experience pole-top fires, which is in agreement with Persadh [5]. However, partial bonding and earthing has resulted in a significant reduction in the number of pole-top fires [7].

The use of steel cross-arms is limited to eliminating fires that occur on the cross-arm by eliminating the fuel source (wood). Fires that occur at the insulation coordination gap are not prevented by the use of steel cross-arms. Using a conductive plate between uncapped post insulators or using capped insulators in addition to correctly bonding the structure will reduce pole-top fires incidents on woodpole cross-arms because of a conductive path provided between the insulator base and the cross-arm as was recommended in [7].

Beutel et al [7]

The work contributed a comprehensive pole-top fires risk analysis of different structure configurations for use in design of new networks. The paper presented a comparative analysis of various structure options for mitigating pole-top fires considering practical utility application. The structure options presented were:

- Fully insulated, i.e. no deliberate bonding and earthing whatsoever as shown in Figure 2.2 a).
- Partially bonded and earthed, as illustrated in Figure 1.1 above.
- Fully bonded and earthed, where all unenergised metal hardware is deliberately bonded together and earthed, as stated by Darveniza, as shown in Figure 2.2 b) [6].

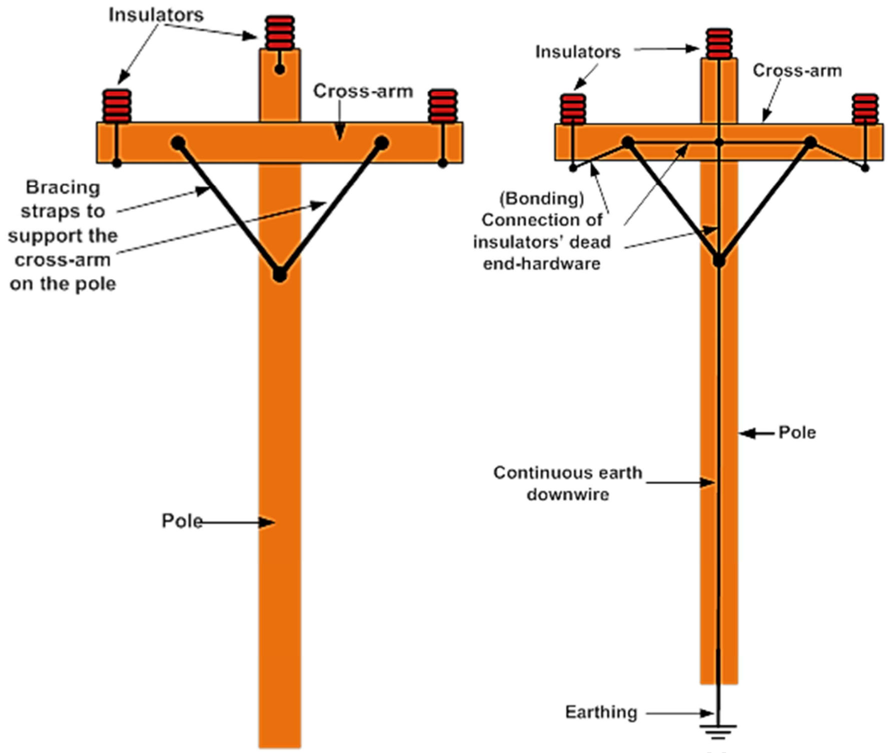


Figure 2.2: Distribution woodpole structure, a) fully insulated, b) fully bonded and earthed

The partially bonded and earthed option was found to offer the best compromise between the various performance criteria in that is has acceptable lightning performance, offers acceptable bird safety and also exhibits improved leakage current performance over the fully insulated configuration. This configuration was therefore used for the present study.

2.1.2 International knowledge

Australian experience

Summarised Australian experience comprised a report from Darveniza who performed extensive work regarding pole-top fires. He reported that pole-top fires can be eliminated by diverting the current completely away from the wood through fully bonding all metal hardware of the structure and earthing using a continuous earth wire [6].

Leakage current of approximately 4 mA to 5 mA was reported to be sufficient to heat a metallic bolt making contact with wood and result in charring of the wood. The finding is comparable to that of Filter in [14] but it is higher than that found by Loxton [5].

Australia experienced the majority of its pole-top fires on structures that were in service for more than 30 years. The reason given is that wood loses its insulation capabilities and becomes brittle over time due to environmental exposure. The wood then burns more easily due to leakage current flow.

The area of a structure that is most susceptible to pole-top fires was reported to be at the wood and metal contact point. On a typical Australian woodpole structure that point is at the king bolt that is securing the cross-arm to the pole, as shown in Figure 2.3. Mitigation methods proposed aim to divert current from the king bolt by using insulated cables for bonding the metal end fittings of the phase insulators to a strap on the pole, as also shown in Figure 2.3, and the use of insulated cables to shunt the leakage current from the phase insulators and king bolt to a termination point lower on the pole – refer to Figure 2.4 [8-9, 13].

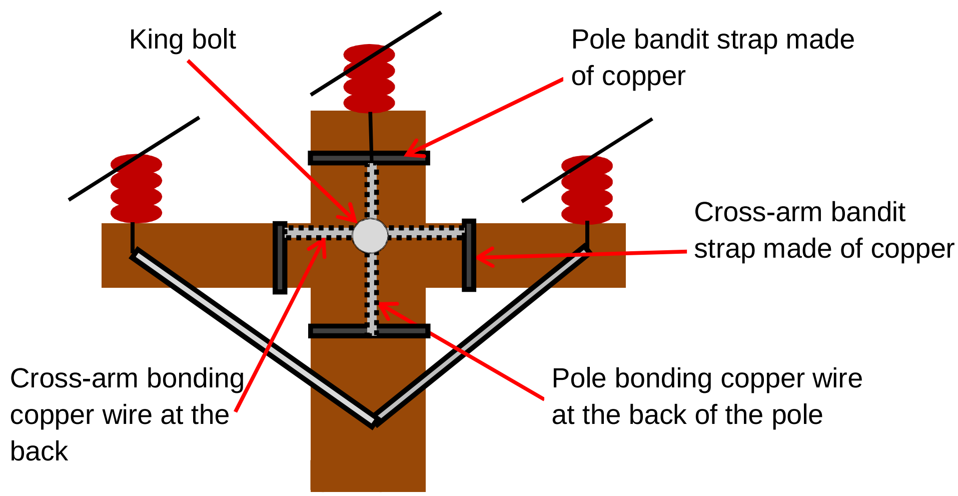


Figure 2.3: Shunting method to divert leakage current away from the king bolt, picture adopted from [8-9]

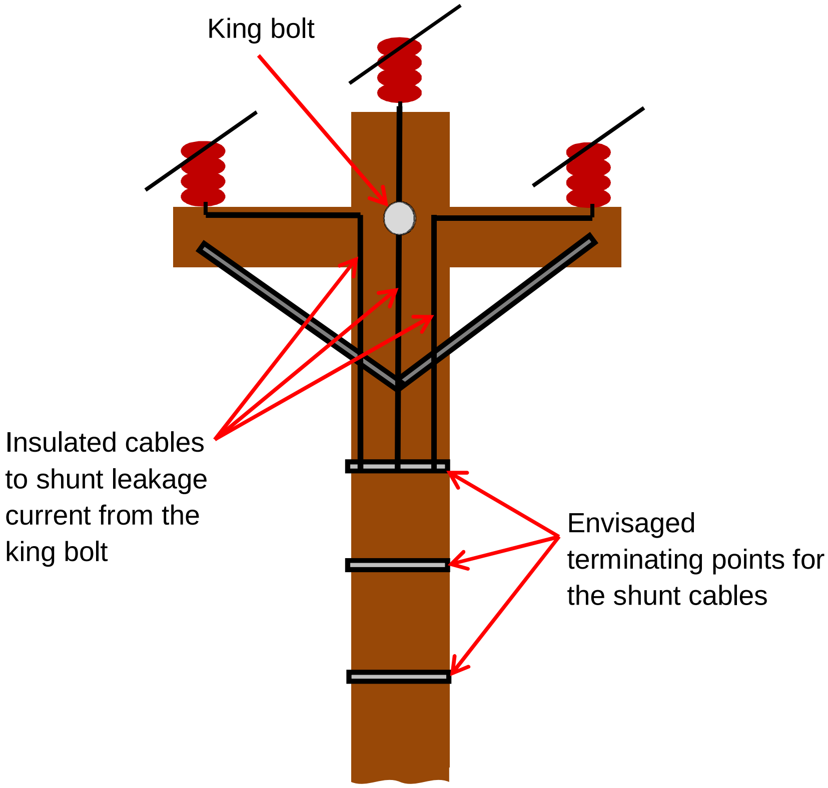


Figure 2.4: Shunting method proposed by Wong et al. picture adapted from [13]

Australian utilities have generally adopted a method of applying a silicone rubber coating on porcelain insulators to limit leakage current magnitude and hence reducing the risk of pole-top fires. The limited lifespan of the silicone rubber coating requires reapplication after a few years and precise workmanship is required. This method is therefore not practical for larger utilities that have long lengths of overhead distribution lines. It was also reported that a plastic-like material could be pasted over the porcelain insulator surface to limit contamination in addition to the use of steel cross-arms instead of wood cross-arms. These methods have the shortcoming in that the king bolt is left vulnerable to leakage current tracking and charring that results in pole-top fires.

Australian researchers, Wong et al. [13], developed a wooden pole model that illustrated that during foul conditions most of the leakage current will flow inside the wood pole. It is as expected due to the moisture increase and retention within the wood and consequently increased conductivity. Furthermore, they proposed a multiphase cable shunting method to divert current away from the intersection point at the king bolt, see Figure 2.4 [11]. This method is not expected to eliminate pole-top fires since the termination points are on the woodpole and leakage current is not diverted away from the pole.

Daveniza [6]

Daveniza's work was published in the 1980's. The book gives details of electrical properties and electrical performance of wood and information pertaining to pole-top fires. Daveniza defined long-term and short-term factors that contribute to the burning of the woodpole structure as: age of the structure, loosened connection at wood and metal interface, pollution on phase insulators, uneven surface wetting, light wetting, circulation of air and other weather conditions. The mechanism described has been confirmed in more recent studies [2-9]. An outcome is that structures with more metal-to-wood interfaces (and by extension more sources of leakage current) are more susceptible to pole-top fires than those with fewer such interfaces. More complex structures also provide more opportunity for poor workmanship than simpler configurations. Figure 2.5 shows examples of complex structures from South Africa.

Daveniza suggested pole-top fires reduction methods such as: shunting (bypassing) zones where ignition is usually initiated, using local bonding of wood and metal interfaces, painting the wood and metal contact section of the woodpole with conductive paint, treating the wood with timber preservative, frequently washing phase insulators, greasing the phase insulators with silicone grease, regular securing of connections at wood-metal interfaces and frequent inspection of insulators. These methods are limited by the amount of manpower available with respect to network length.

Figure 2.5: Examples of complex woodpole distribution structures

Filter [14]

Filter investigated the susceptibility of power utility woodpoles to fire. He tested pole stub specimens with various treatments such as water-borne preservatives Ammonia Copper Arsenate (ACA) and Chromate Copper Arsenate (CCA) and the oil-borne preservative pentachlorophenol. The outcomes were that the inception of fire on a woodpole is influenced by the type of wood species, moisture content and preservative treatment. It was reported that a fire took longer to ignite in poles that were treated with water-borne preservatives. The chance of leakage current flowing on the surface of poles treated with water-borne preservatives was reported to be high during wet weather conditions. Oil-borne poles exhibited burning with deep distinct charred tracking, in contrast to water-borne poles that showed a shallow but wider burned track. South African power utility Eskom uses the oil-borne preservative, creosote, but the effect of the type of wood preservative is outside the scope of this project.

Wareing [15]

The work reported the upgrade of a distribution line in Oman, Middle East. One of the many challenges experienced with the line was pole-top fires due to severe desert and corrosive sea conditions and also pollution from diesel plants. The distribution line comprised wood poles and porcelain insulators.

To address this issue, the power utility took a decision to completely replace the line and do away with woodpoles and porcelain insulators. The new line consisted of self-supporting concrete poles, steel cross-arms and silicone rubber insulators. The upgrade completely eliminated pole-top fires. However such a line is not common practice for electricity distribution in rural and isolated areas for cost reasons. Hence, this solution has not been extensively used in South Africa.

2.2 Individual Insulator Testing

The measurement and analysis of leakage current is the basis for determining the performance of individual insulators. Publications reviewed use leakage current measurements as the determining factor for the performance of insulators.

2.2.1 Insulator standards

SANS 60815 [10]

Details of artificial pollution testing of insulators and their selection and design are covered. Insulator material that is traditionally selected is glazed porcelain or glass, with polymer insulators as an alternative should the former not meet environment, performance or system constraints.

For a standard porcelain insulator profile, pollution accumulated on horizontally mounted insulators can be expected to be light compared to vertically mounted insulators. Insulators that are mounted horizontally have a wide surface area that is exposed allowing the surface to be effectively naturally cleaned by rain and wind [SANS 60815-2 p.10]. Pollution collection was reported to vary for different profiles of polymeric insulators. Furthermore, the effectiveness of the shape is dependent on the type of pollution the insulator is exposed to. The effect of insulator orientation is stated as not obvious and that the insulator type and size will contribute significantly to the performance. Polymeric insulators with open profiles that are used for horizontal and vertical application can be expected to have similar self-cleaning capabilities. Shed-to-shed spacing as a limiting factor was highlighted as important when a polymeric insulator profile is designed so that shed-to-shed arcing is prevented. Polymeric insulators are reported as prone to environmental and electric field degradation over their service life which can reduce their service lifespan.

Cigrè Brochure No 158-2000 [16]

The document reports that natural cleaning by wind or rain is effective when insulators are mounted horizontally and the effectiveness of horizontal orientation is influenced by the area in which the insulators are used and on the type of pollution present. Polymer formulation and production are factors that influence material performance. Therefore insulator material choice should take cognisance of the quality of polymer additives and manufacturing.

Porcelain or ceramic insulators with alternating sheds were stated to have better leakage current performance than porcelain insulators with uniform sheds. Large shed-to-shed spacing can be applied to improve performance. For polymeric insulators it was indicated that alternating long-and-short shed profiles exhibited improved leakage current performance than uniformly shaped polymeric insulators. No substantial difference in leakage current performance between horizontal and vertically mounted silicone rubber insulators was reported.

2.2.2 Insulator material

Vosloo [12]

Vosloo provides details of leakage current performance of insulators exposed to natural South African coastal conditions at the Koeberg Insulator Pollution Test Station (KIPTS). The work comprised evaluation and comparison of different insulator materials. Six new insulators were tested under natural pollution for a year. Their overall leakage current performance was ranked as follows: resistive/semi-conducting glazed porcelain with the lowest leakage level followed by Room Temperature Vulcanized (RTV) silicone rubber coated porcelain, High Temperature Vulcanised (HTV) silicone rubber, EPDM, glazed porcelain and lastly cycloaliphatic epoxy resin as having the highest leakage current level. Silicone rubber insulators are expected to have the best performance provided environmental factors have not degraded the material's hydrophobicity.

El—Hag et al. [17]

The influence of silicone rubber insulator profile is evaluated. It is showed that the diameter of the insulator sheds and the shed inter-space distance has a significant role in determining the leakage current performance of a silicone rubber insulator. This supports the premise that shed diameter and spacing need to be selected appropriately depending on the application and considering environmental conditions. In addition, the angle of the shed incline position has an effect on the level of pollution collected in between the sheds and how effectively they are washed. The paper raises the expectation that short and wide insulators have better leakage current performance.

Charzan et al. [18]

The paper reports on tests performed on porcelain and HTV silicone rubber insulators. The tests were conducted at an outdoor facility in South Africa at KIPTS. It demonstrated that leakage current performance of a silicone rubber insulator is better than that of a porcelain insulator. However, it revealed that the finding is not absolute and the leakage current performance of the two insulator materials was similar when they were subjected to light industrial pollution. Furthermore, silicone rubber insulators performed worse than porcelain insulators due to the effect of season and time of day. It was observed that porcelain insulators were cleaner than silicone insulators meaning pollution was more easily washed from porcelain insulators than from silicone rubber insulators by rain. In addition, during a dry spell when slightly wet conditions were present due to high humidity, silicone rubber insulators may have absorbed moisture that resulted in the accumulated pollution becoming conductive and high leakage currents flowing compared to that flowing on porcelain insulators.

Sorgvist et al. [19]

Measurements performed on porcelain insulators with RTV silicone rubber coating are reported. Some insulators were exposed to indoor conditions and some were exposed to natural conditions in the field. The results show that the RTV silicone rubber coating deteriorated relatively quickly due to environmental factors. In nine years the RTV coating can be expected to gradually lose its hydrophobicity. The use of RTV coating as a retrofit solution mitigating pole-top fires is observed as a laborious task taking cognisance of the length of distribution networks and the life expectancy of the line. Moreover such a solution will not be sustainable especially for areas with heavy pollution, because re-application is necessary after a few years. Hence the laboratory measurements on reduced scale woodpole structures reported subsequently did not include this case.

2.2.3 Insulator profile and orientation

Wieczorek et al. [20]

Aging of composite insulators with HTV silicone rubber housing was investigated. The insulators had different shed slope angles and were tested in a laboratory fog and rain chamber. Under rain conditions, when composite insulators are changed from the vertical position to the horizontal position, a large area of the insulator surface is uniformly exposed to wetting by the rain and may lead to a wide conductive area surface and ultimately result in the flow of high leakage current. This effect is applicable for continuous rain falling directly over an insulator with matching shed diameters and short shed to shed interspace less than or equal to 30 mm. This finding is contrary to what is expected from [10] and [11] regarding porcelain insulators. One may still argue that the large area of the insulator that is uniformly exposed to rain will likely be washed cleaner and lead to a high surface resistance contributing to less leakage current. It may be found that over the four seasons, silicone rubber insulators mounted horizontally have better leakage current performance compared to vertically mounted ones. Hence the contents of the research included full scale measurements over a period of a year. The effect of horizontal or vertical position is not significant under fog conditions. This finding concurs with other findings in [10] and [15] that polymeric insulators have similar leakage current performance for vertically mounted insulators and horizontally mounted insulators.

2.2.4 Leakage current measurement method

Pylanoris [21]

Information regarding test methods for insulators and analysis of leakage current as a means to determine the condition of the surface of the insulator is presented. Laboratory tests for insulators such as the inclined-plane test, rotating wheel dip test, salt-fog test, clean-fog test and ice test are explained. The salt-fog test is applicable for simulating coastal pollution.

Different analysis techniques useful in understanding the measured leakage current were discussed. The paper gave six basic leakage current analysis methods, 1) basic electrical value calculation, 2) advanced analysis technique in the time domain, 3) surface activity based leakage current waveform decomposition, 4) frequency analysis, 5) pattern recognition and 6) multi resolution analysis technique. For this research, the total r.m.s. leakage current and frequency analysis was used in analysing the measured leakage current. The total r.m.s. leakage current indicates the square-root of the average peak leakage current values. Frequency analysis was adopted so that the harmonic content may be used for interpreting the electric discharge arc activity present on the structure.

2.3 Summary

A review of available literature regarding pole-top fires and testing of individual insulators was presented, with the purpose of determining previous experience with respect to performance of individual insulator material, profile and orientation and summarising the state of the art with respect to mitigation against pole-top fires.

3 LABORATORY MEASUREMENTS ON A REDUCED SCALE WOODPOLE STRUCTURE

Laboratory measurements on a reduced scale woodpole distribution line structure are presented. Measurements were conducted for various insulator types and arrangements on the cross-arm. The objective was to determine the structure leakage current performance in order to have a baseline for the effect that insulator orientation, insulator material and insulator profile have on the performance.

3.1 Setup

Some of the measurements were performed at an inland facility - Eskom's "corona cage" testing station. The tests were also performed at a coastal facility, KIPTS. At both facilities, the tests were performed in an outdoor chamber.

The tests at the corona cage explored the case of a structure with porcelain post insulators all positioned vertically on the woodpole cross-arm and the case of the same structure with the two outer phase insulators re-positioned to be horizontal. A three-phase supply from three 220 V/11 kV single phase transformers was used to energise the structure with 11 kV phase-earth. For both cases salt solution was sprayed to pollute the insulators and the structure.

The tests at KIPTS were performed on the same structure previously used at the corona cage. The cases investigated were of the structure with porcelain post insulators all orientated vertically, followed by tests on the same structure with HTV silicone rubber post insulators all positioned vertically. The tests concluded with the same structure but with the two outer phase insulators being HTV silicone rubber long rod insulators and the middle insulator a post insulator. For each case, 22 kV phase-phase supply was used to energise the structure. Sea water was sprayed for polluting the structure and insulators and a few measurements were taken. Thereafter a salt solution was sprayed on the insulators and structure and the concluding set of measurements were captured.

Figure 3.1 shows a diagram of the test structure and the measurement setup. An envisioned equivalent circuit is shown in Figure 3.2. The phase insulators' surface resistance and the woodpole's surface resistance are expected to vary as a result of pollution collection and moisture and therefore alter the structure leakage current performance accordingly.

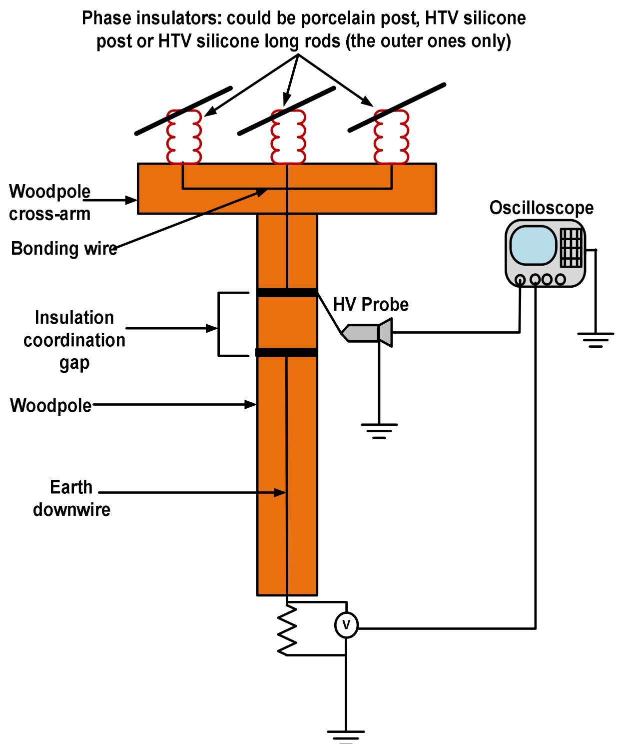


Figure 3.1: Typical woodpole structure layout of measurement setup

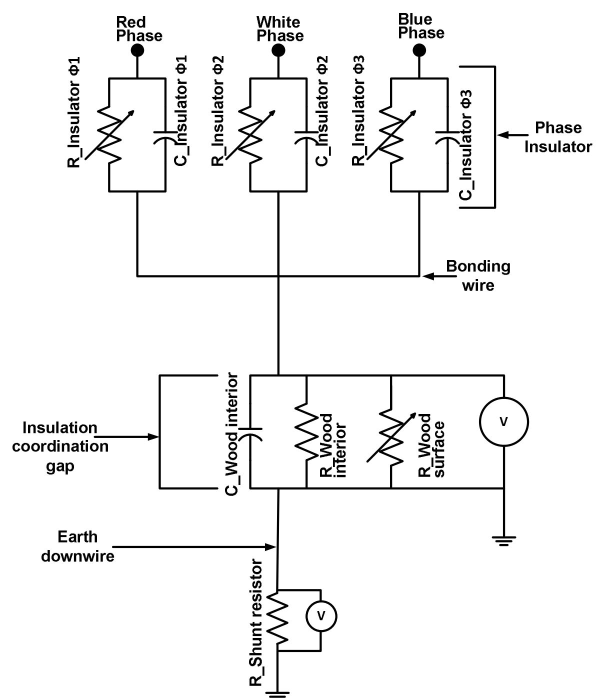


Figure 3.2: Circuit model for measurement setup

The test apparatus used for the measurement are as listed below:

1. Battery powered multichannel oscilloscope
2. Single ended HV measuring probe
3. Shunt resistors
   i. Corona cage: 10 kΩ resistor
   ii. KIPTS: 120 Ω resistor
4. MV phase insulators, shown in Figure 3.3. Their data sheets are found in Appendix B.
   i. Three capped porcelain post insulators
   ii. Three HTV silicone rubber post insulators
   iii. Two HTV silicone rubber long rod insulators

a) b) c)

Figure 3.3: Insulators used for the laboratory test set up a) porcelain post capped insulator, b) HTV silicone post capped insulator, c) HTV silicone long rod insulator

5. Two new Eskom distribution woodpoles treated with creosote
   i. Vertical woodpole: 1 m x 30 cm x 10 cm
   ii. Woodpole cross-arm: 2 m x 30 cm x 10 cm
6. Structure accessories (galvanised threaded rods, spindles, copper stranded cable, washers, nuts, U-nails, bonding clips, middle phase bracket for insulator, bandit strip)

7. Standoff insulators
    i. Corona cage: two 132 kV porcelain standoff insulators
    ii. KIPTS: one 66 kV porcelain standoff insulator and one 66 kV RTV silicone rubber coated porcelain standoff with silicone rubber extended sheds
8. Earth stick and a switching kit

The structure was partially bonded through a 500 mm woodpole gap (referred to as an insulation coordination gap) and earthed via an earth downwire connected to the local earth point.

Stand-off insulators were used as pedestals for mechanical support and to suspend the reduced scale structure safely from earth. The suspension of the structure was necessary to facilitate leakage current measurement since the downwire was connected to the bottom of the structure with a U-nail.

3.2 Methodology

IEC 60507 recommends artificial pollution testing of insulators to be performed in a fog chamber with salt-fog or clean-fog. Due to the non-existence of a fog chamber with a three-phase supply and dimensions to accommodate the woodpole structure, test measurements were adopted for a salt solution sprayed on the structure and insulators in an outdoor live chamber. The salt solution salinity was within the recommended salinity values.

There are hazards associated with working in a live chamber and a test procedure was developed to conduct the measurements in a safe manner following high voltage regulations and acceptable high voltage test practice. The procedure was developed in collaboration with Eskom Research Testing and Development and the responsible person for the test facility. The contents of the procedure comprise safe clearance distance for the phase insulators and measurement apparatus. The sequence and progression of performing measurements is outlined for events: before energising structure, when energising the structure, when the structure is energised and when de-energising the structure. The procedure is found in Appendix C.

3.2.1 Measurements performed

Current measurement using a shunt resistor was adopted. The earth downwire was attached underneath the main woodpole with a U-nail and connected in series with the shunt resistor. A 10 kΩ shunt resistor was used at the corona cage and a 120 Ω shunt resistor was used at KIPTS. A resistor with a high value was used at the corona cage because of the supply's earth leakage limitations and that environmental conditions at the site were not conducive for high leakage currents. At KIPTS higher leakage current levels due to sea breezes or possible high humidity levels were expected to be measured hence a smaller shunt resistor was used.

A single-ended HV probe was used for voltage measurements at the insulation coordination gap. The probe was connected to the top bandit strap of the insulation coordination gap.

A battery powered multichannel oscilloscope was used for measurements and storage. The scope's channels were connected to a common earth by connecting the earth point at the back of the scope to the local earth point.

Pollution sprayed on the structure was selected to be sea water and salt solution because they represent Type B pollution that is synonymous with coastal pollution and most of the pole-top fires in South Africa are reported to occur near the coast in the KZN region. Pollution was sprayed onto the structure and onto the phase insulators using a commercial spray gun. Application of 10 sprays was done to achieve uniform wetting conducted from the same position, height and angle relative to the structure and phase insulators.

3.2.2 Measurement sequence

The tests were conducted as follows:

<u>First set</u>

1. Install phase insulators on the cross-arm.
2. Ensure that all connections were secure and making good contact and confirm the functional integrity of the measuring apparatus.
3. Prepare phase insulators and clean the standoff insulators.
4. Record weather details. (Obtained from the Koeberg Meteorological Tower)
5. Energise the structure for measurement with the structure dry and the insulators dry (conductive pollution not sprayed on). Record measurements.
6. De-energise, isolate, earth and discharge the structure.
7. Spray artificial pollution on the structure and insulators using sea water.
8. Energise the structure. Record measurements.
9. De-energise, isolate, earth and discharge the structure.
10. Re-spray with sea water after a few minutes when the first deposit is dry.
11. Energise the structure. Record measurements.
12. Repeat point 6 to point 11.
13. Move to last set.

Last set

14. De-energise, isolate, earth and discharge the structure.
15. Spray artificial pollution on the structure and insulators using salt solution.
16. Energise the structure. Record measurements.
17. De-energise, isolate, earth and discharge the structure.
18. Re-spray with salt solution after a few minutes when the first deposit is dry.
19. Energise the structure. Record measurements.
20. Repeat point 14 to point 19.
21. De-energise, isolate, earth and discharge the structure.
22. Change insulators on the cross-arm.
23. Repeat point 2 to point 23 until measurements are made for all types of phase insulators.

3.3 Measurement Results

Structure leakage currents are compared both in the time domain and in the frequency domain. The difference in r.m.s. values gives information on the heating of the structure that may lead to woodpole ignition. The spectrum indicates arcing activity on the structure and possible tracking on the woodpole.

3.3.1 Insulator orientation effect

The effect of insulator orientation was determined by comparing porcelain insulators either mounted vertically or mounted horizontally. Figure 3.4 and Figure 3.5 show the test structure setup. The measurements were all carried out at the corona cage.

One of the outcomes from the literature review was that insulator orientation has minimal effect on the leakage current for silicone rubber insulators. HTV silicone rubber insulators were therefore not tested. Porcelain insulators were selected because of the common practice of using them on Eskom distribution structures. Moreover, the testing of porcelain insulators was influenced by the expectation that the effect of insulator orientation is impacted by the natural cleaning which is effective particularly on porcelain insulators because they wash easily. Results will therefore be conclusive with porcelain insulators.

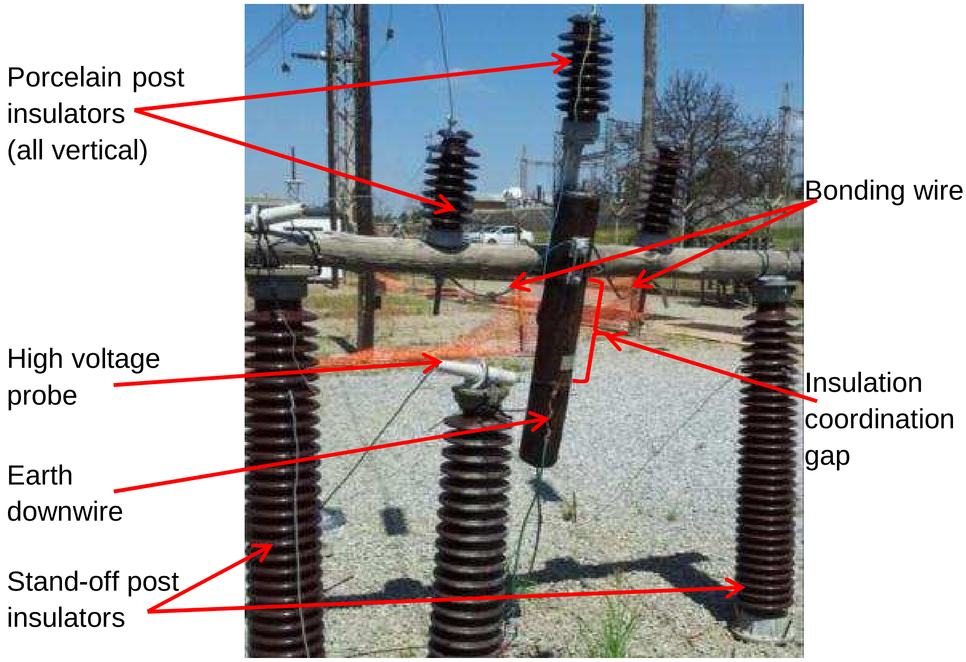


Figure 3.4: Insulator orientation evaluation with all the porcelain post insulators positioned vertically

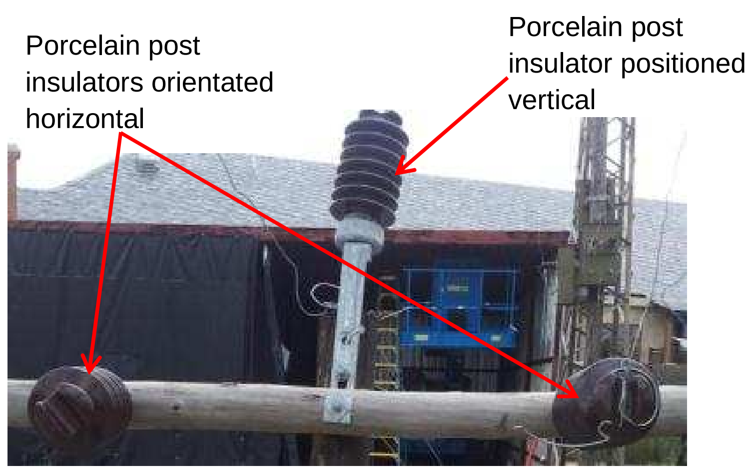


Figure 3.5: Insulator orientation evaluation with two porcelain post insulators positioned horizontally (same structure setup as Figure 3.4, two insulators' position changed to horizontal)

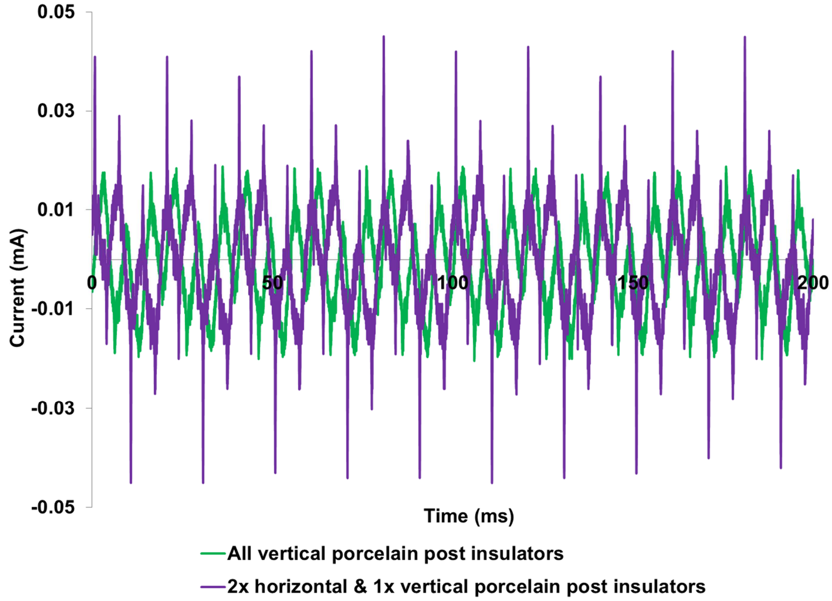
Results

Measurements to determine the effect of insulator orientation were obtained for the conditions listed in Table 3.1. The weather information shown is comparable for each case and therefore the climatic conditions are not expected to influence the structure leakage current.

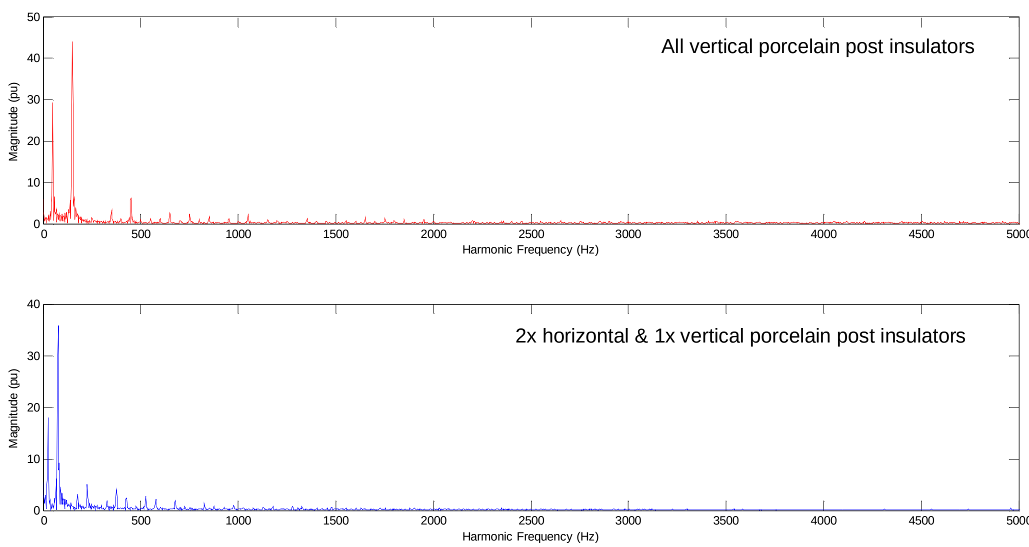
Table 3.1: Conditions under which measurements were taken for investigating effect of insulator orientation

Case investigated	Temperature (°C)	Humidity (%)	Wind speed (m/s)	Pollution applied	Insulator condition before testing
Structure with all vertical porcelain post insulators	22.3	37	0.7	Sprayed on salt solution (salinity of 10 kg/m^3)	Insulators cleaned with pure water
Structure with 2x horizontal and 1x vertical porcelain post insulators	24.2	32.5	0.8		

Figures 3.6, 3.7, and 3.8 show the measured leakage current waveforms and the corresponding spectra.



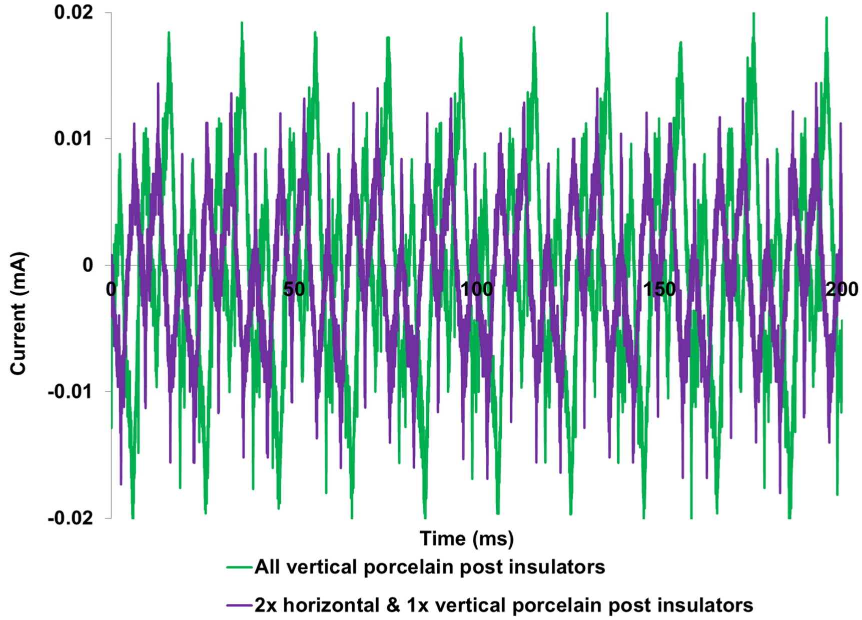
a)



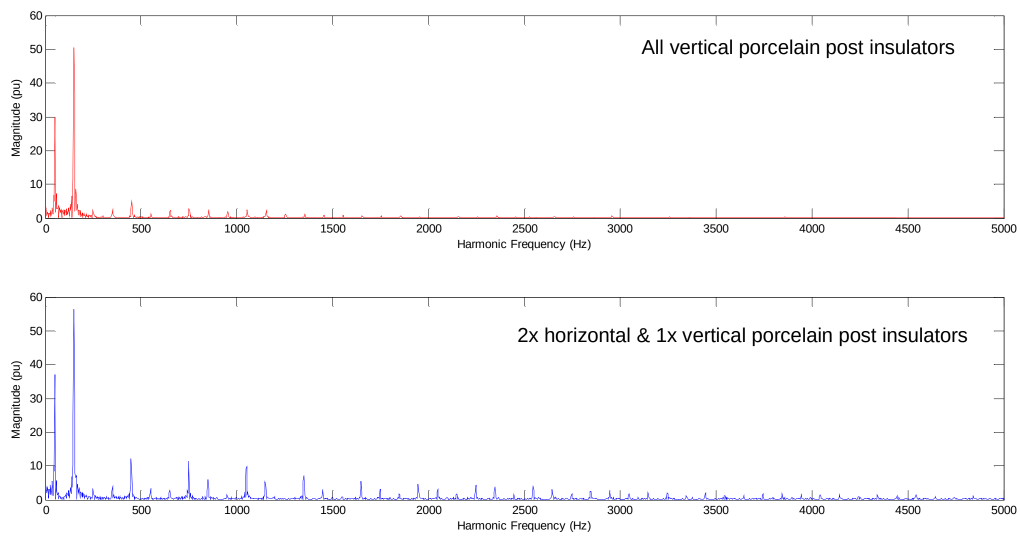
b)

Figure 3.6: Insulator orientation evaluation, structure sprayed with salt solution (salinity of 10 kg/m^3): a) Time domain, b) Frequency domain

Figure 3.6 a) shows little difference between the waveforms for the case with horizontal porcelain post insulators and that with vertical post insulators. The two cases had a total r.m.s. leakage current of 0.009 mA and 0.01 mA respectively. This illustrated that both structures experienced the same heating effect and would have similar risk of wood ignition within the woodpole, leading to pole-top fires.



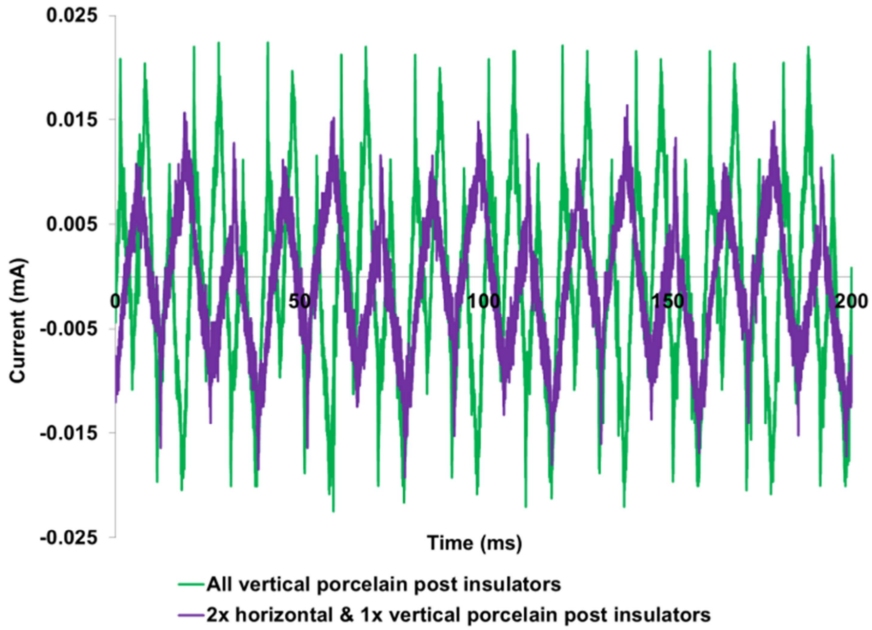
a)



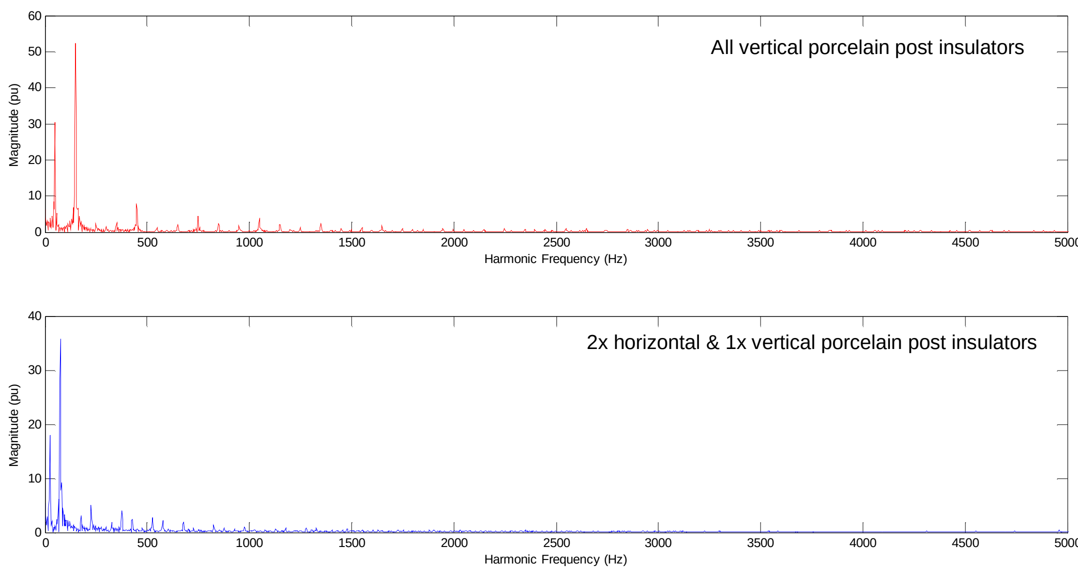
b)

Figure 3.7: Insulator orientation evaluation, structure re-sprayed with salt solution after few minutes when first deposit was dry (salinity of 10 kg/m^3): a) Time domain, b) Frequency domain

Results when the structure was re-sprayed after the previous deposit dried are shown in Figure 3.7. The case with horizontal insulators recorded a total r.m.s. leakage current of 0.005 mA and the case with all vertical insulators recorded a total r.m.s. leakage current of 0.008 mA. The presence of higher frequency components may suggest arcing activity on the structures.



a)



b)

Figure 3.8: Insulator orientation evaluation, structure re-sprayed with salt solution after few minutes when second deposit was dry (salinity of 10 kg/m^3): a) Time domain, b) Frequency domain

Figure 3.8 shows results when the structure was re-sprayed after the second deposit dried. Total r.m.s leakage current of 0.006 mA was recorded for the case with horizontal insulators and 0.009 for the case with all vertical insulators.

Summary of outcomes

Observations made from the results showed that structure leakage current performance is improved for the case with two horizontal post insulators.

3.3.2 Insulator material effect

To evaluate the choice of insulator material a case of the structure with all vertical porcelain post insulators and a case with all vertical HTV silicone post insulators were compared. Figure 3.9 shows the setup for the case with all porcelain post insulators and Figure 3.10 shows the setup for the case with all HTV silicone post insulators.

The measurements were conducted at KIPTS. The structure and insulators were sprayed with pollution comprising sea water for the first few measurements and thereafter sprayed with salt solution for the concluding set of measurements.

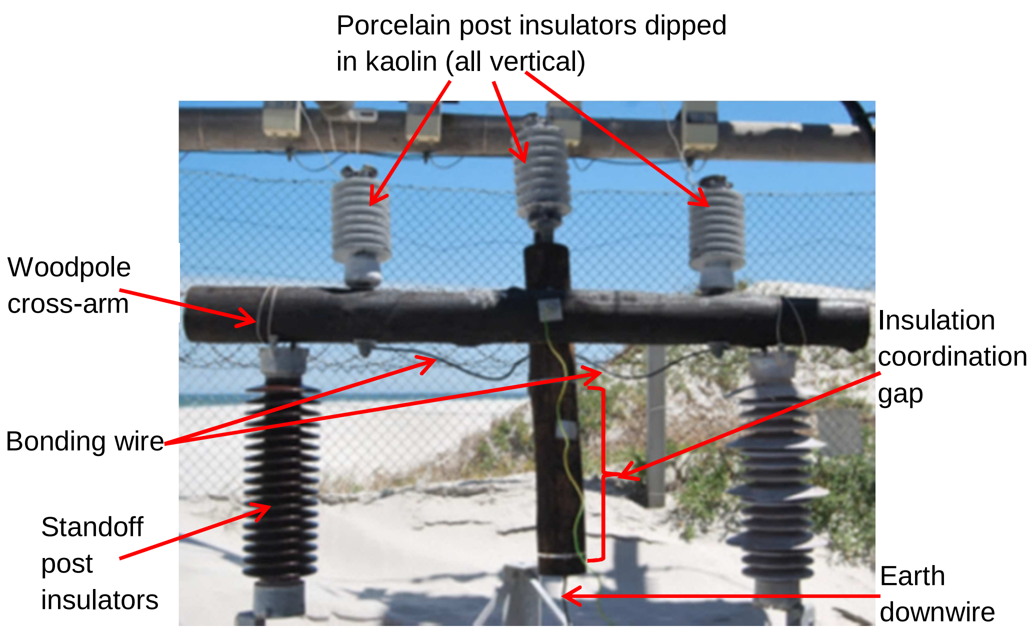


Figure 3.9: Insulator material evaluation with only porcelain post insulators

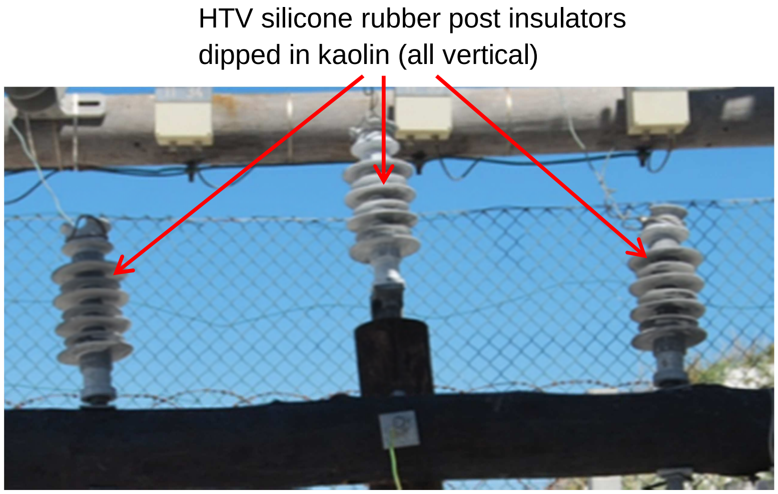


Figure 3.10: Insulator material evaluation with only HTV silicone rubber post insulators (same structure setup as Figure 3.9, insulators changed to HTV silicone rubber post)

The two insulator materials were chosen as porcelain and silicone rubber because porcelain post insulators are extensively used on Eskom's distribution structures, particularly those experiencing pole-top fires and silicone rubber insulators are considered as an alternative for porcelain when improved pollution performance is required [10].

Silicone rubber insulators are known for their hydrophobicity and for this reason merely spraying a salt solution on them would have yielded very low levels of leakage current. Hence all the insulators were cleaned with pure water and uniformly dipped in a kaolin solution mixture with tap water (40g/l was recommended [28]) and left to completely dry before the measurements in order to yield a sufficient magnitude of leakage current during testing. Therefore, insulators had heavy pollution which is the case when the risk of pole-top fires occurring is at its highest.

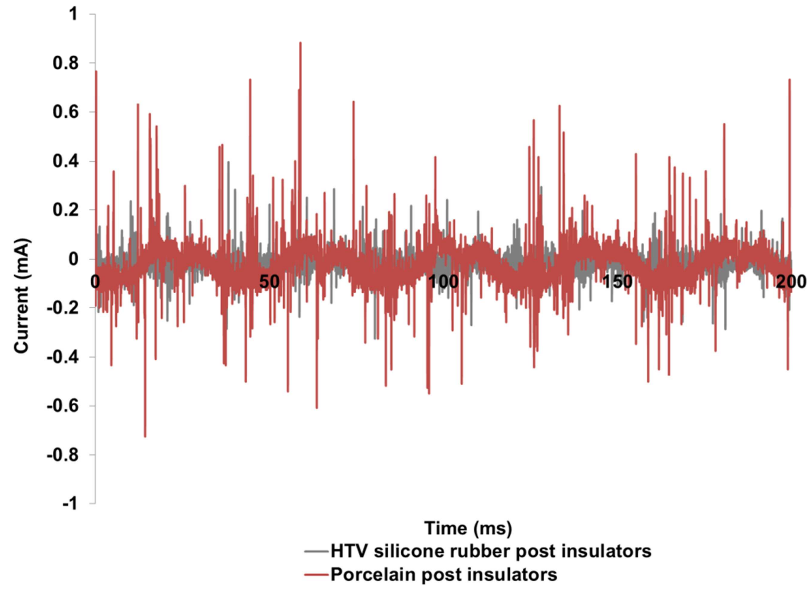
Results

Conditions under which the measurement results were obtained are given in Table 3.2. The weather information shown is comparable for each case. The humidity level is high and the temperature is in the low twenties. This condition is conducive for raising the conductivity of the surface pollution and the formation of dry bands. It is therefore expected that the structure may have increased arc activity and the time domain waveforms will have spikes and the spectrum will also have a large harmonic content.

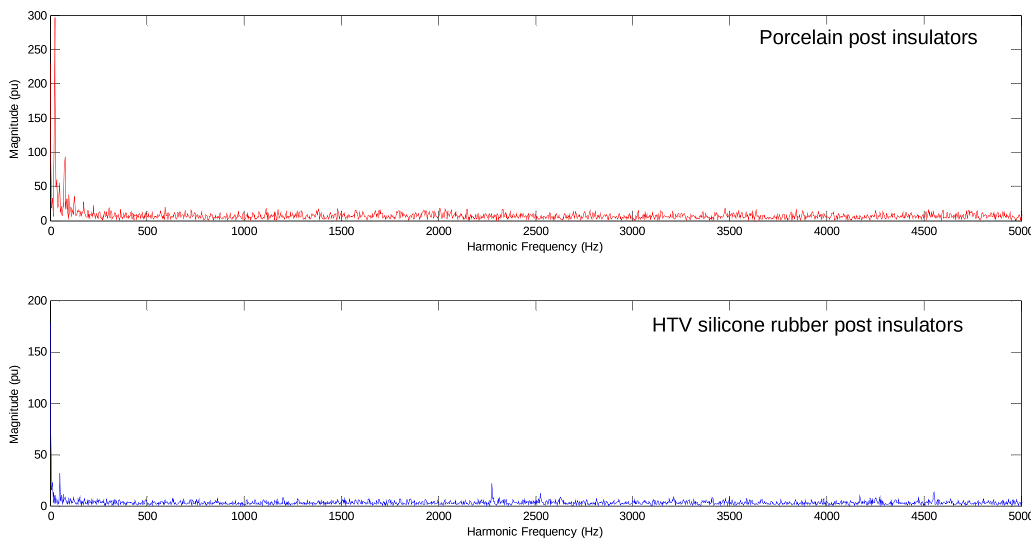
Table 3.2: Conditions under which measurements were taken for investigating effect of insulator material

Case investigated	Temperature (^{o}C)	Humidity (%)	Wind speed (m/s)	Pollution applied	Surface condition before testing
Structure with all vertical HTV silicone rubber post insulators	20.1	79	4.4	Sprayed on sea water (salinity of 40 kg/m^3) for first set	Insulators cleaned with water and dipped in kaolin solution
Structure with all vertical porcelain post insulators	20.1	79	4.4	Sprayed on salt solution (salinity of 112 kg/m^3) for last set	

Figures 3.11, 3.12, 3.13, 3.14 and 3.15 show the measured leakage current waveforms and the corresponding spectra.



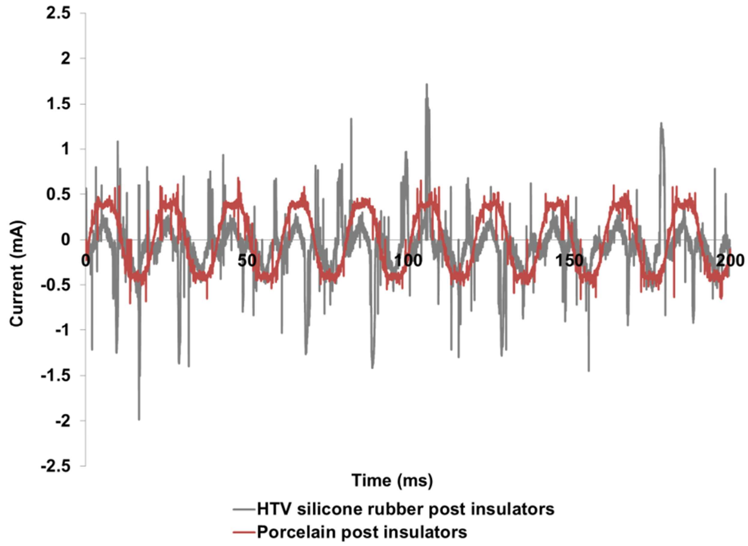
a)



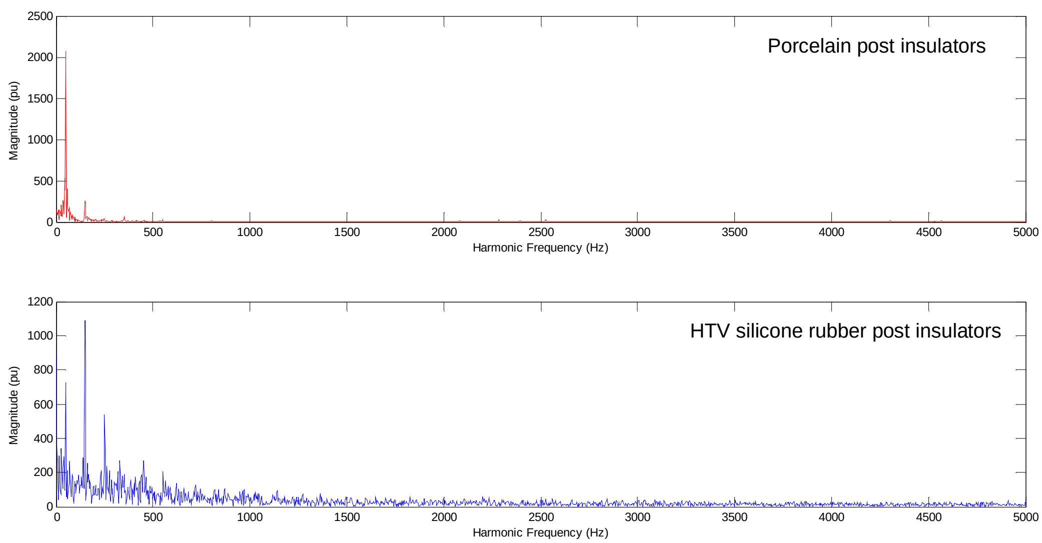
b)

Figure 3.11: Insulator material evaluation, structure dry and dry insulators: a) Time domain, b) Frequency domain

Figure 3.11 shows that during dry conditions the structure had a total r.m.s. leakage current of 0.075 mA for the porcelain insulators and a total r.m.s. leakage current of 0.034 mA for the silicone rubber insulators.



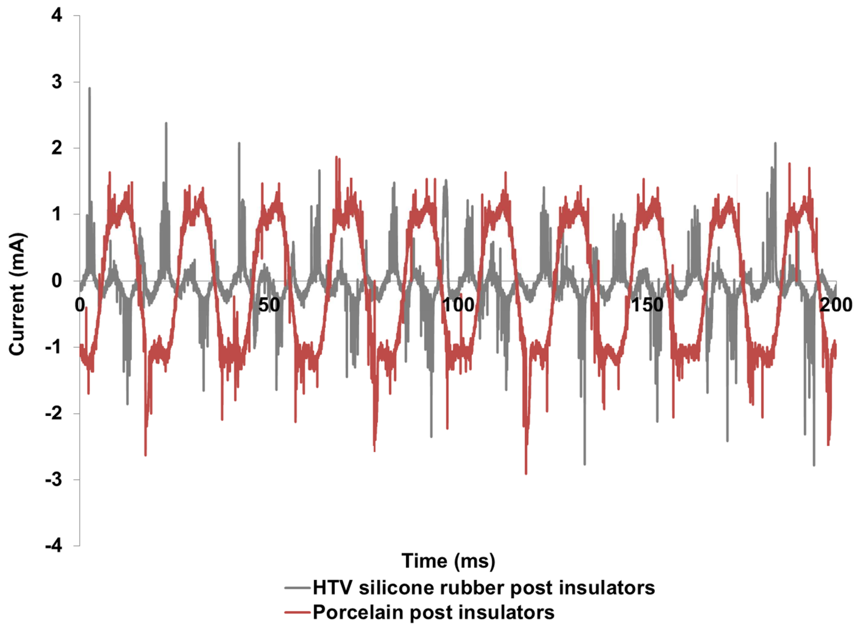
a)



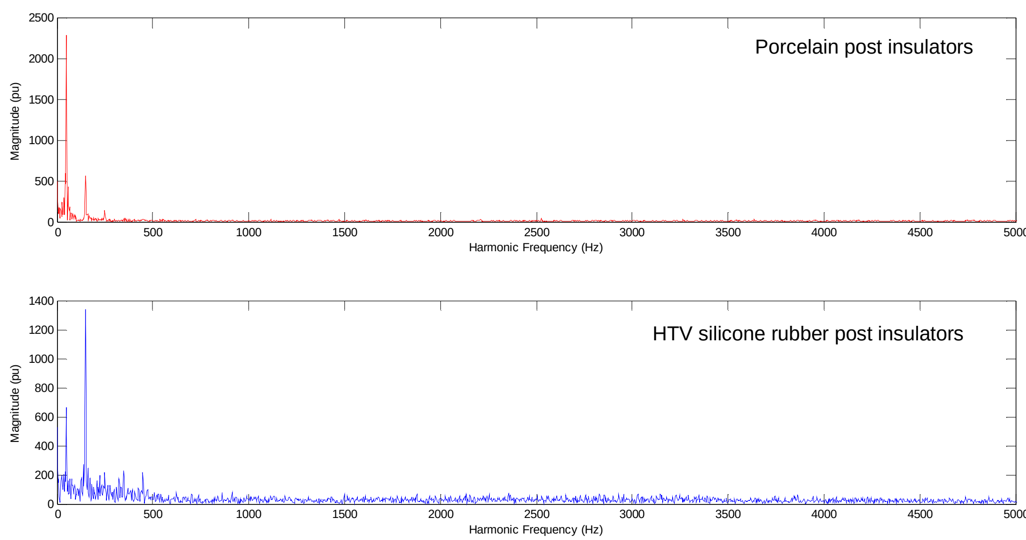
b)

Figure 3.12: Insulator material evaluation, structure sprayed with sea water (salinity of 40 kg/m3): a) Time domain, b) Frequency domain

Results displayed in Figure 3.12 show a total r.m.s. current of 0.333 mA for the silicone rubber insulators and a total r.m.s. current of 0.337 mA for the porcelain insulators. Arcing activity is indicated in the spectrum waveform for the silicone rubber insulators shown by the presence of higher frequency components.



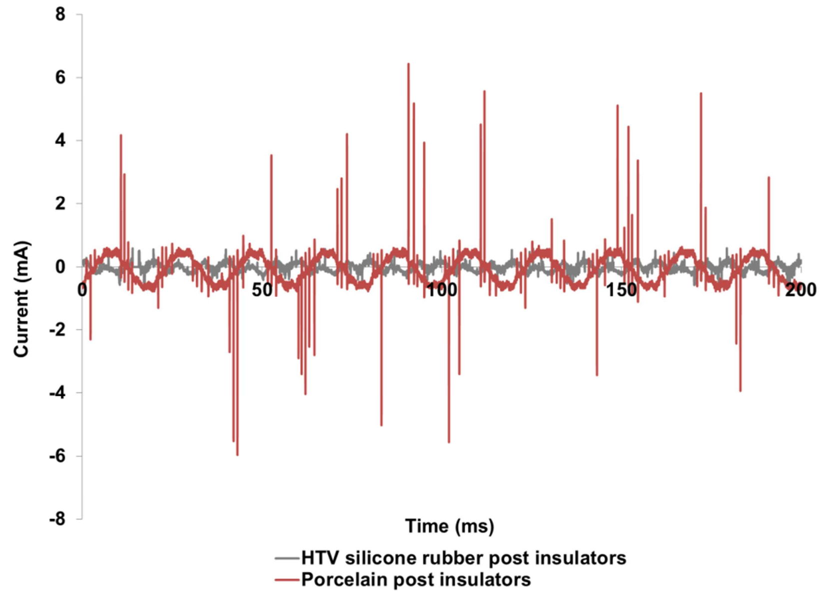
a)



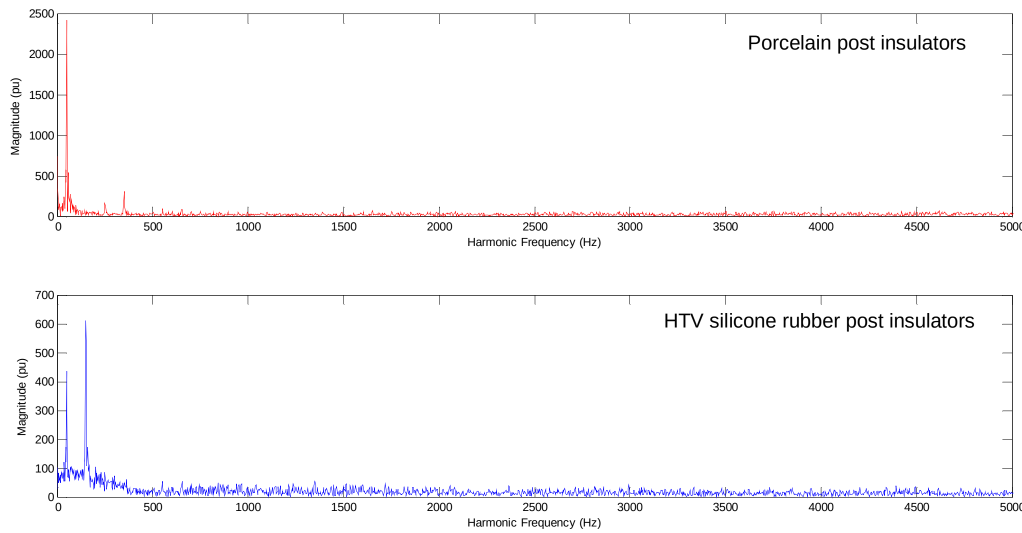
b)

Figure 3.13: Insulator material evaluation, structure re-sprayed with sea water (salinity of 40 kg/m^3): a) Time domain, b) Frequency domain

Figure 3.13 shows subsequent total r.m.s. leakage current measurements of 0.324 mA for the silicone rubber insulators and 0.952 mA for the porcelain insulators. The former had better leakage current performance.



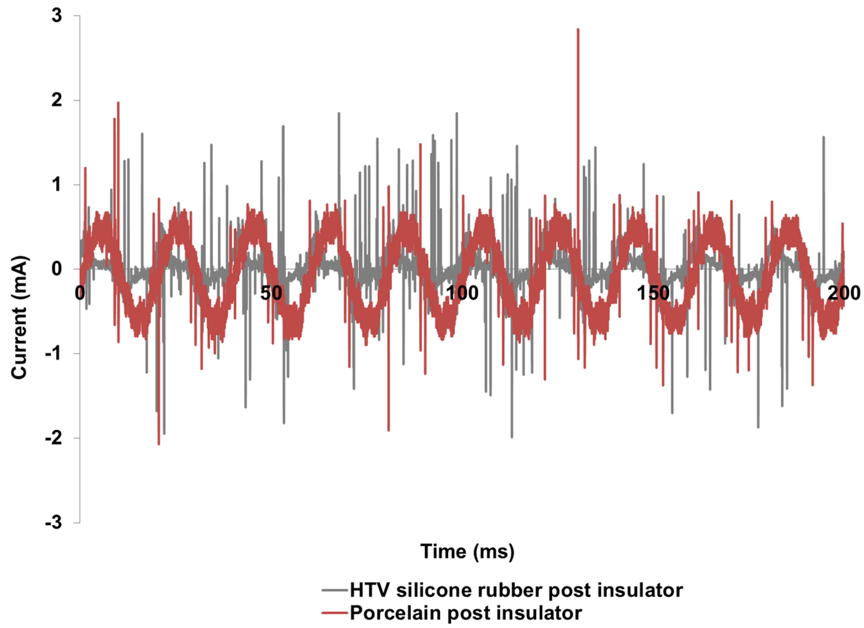
a)



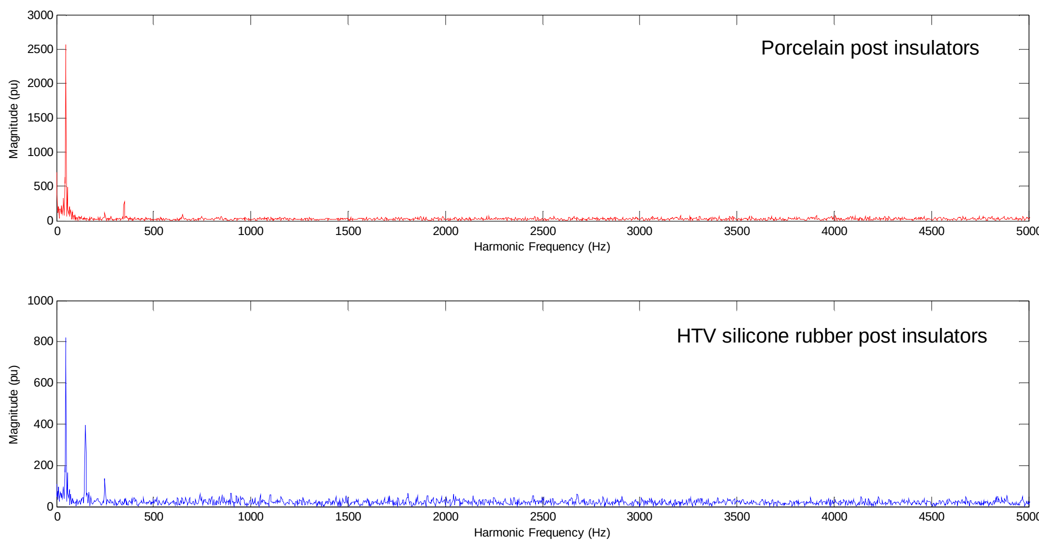
b)

Figure 3.14: Insulator material evaluation, structure sprayed with salt solution (salinity of 112 kg/m^3): a) Time domain, b) Frequency domain

Figure 3.14 shows the total r.m.s. leakage current of 0.173 mA for the silicone rubber insulators and 0.492 mA for the porcelain insulators.



a)



b)

Figure 3.15: Insulator material effect evaluation, structure re-sprayed with salt solution (salinity of 112 kg/m^3): a) Time domain, b) Frequency domain

Figure 3.15 shows the total r.m.s. leakage currents of 0.202 mA for the silicone rubber insulators and 0.43 mA for the porcelain insulators. It is shown that the leakage current is lower for the case with silicone rubber insulators compared to the case with porcelain insulators.

Summary of outcomes

Observations made from evaluating the effect of insulator material were that the leakage currents for all pollution salinity instances (sea water and salt solution) were lower for silicone rubber insulators compared with porcelain insulators – as expected. This indicates that the structure can be expected to have improved leakage current performance and the risk of pole-top fires occurring may be reduced by insulator material choice in conjunction with certain bonding arrangements.

3.3.3 Insulator profile effect

The effect of insulator profile was assessed by comparing a structure with all HTV silicone rubber post insulators and a structure where the two outer phase insulators were replaced with HTV silicone rubber long rod insulators. The setups used for the measurement are shown in Figure 3.16 and Figure 3.17 respectively.

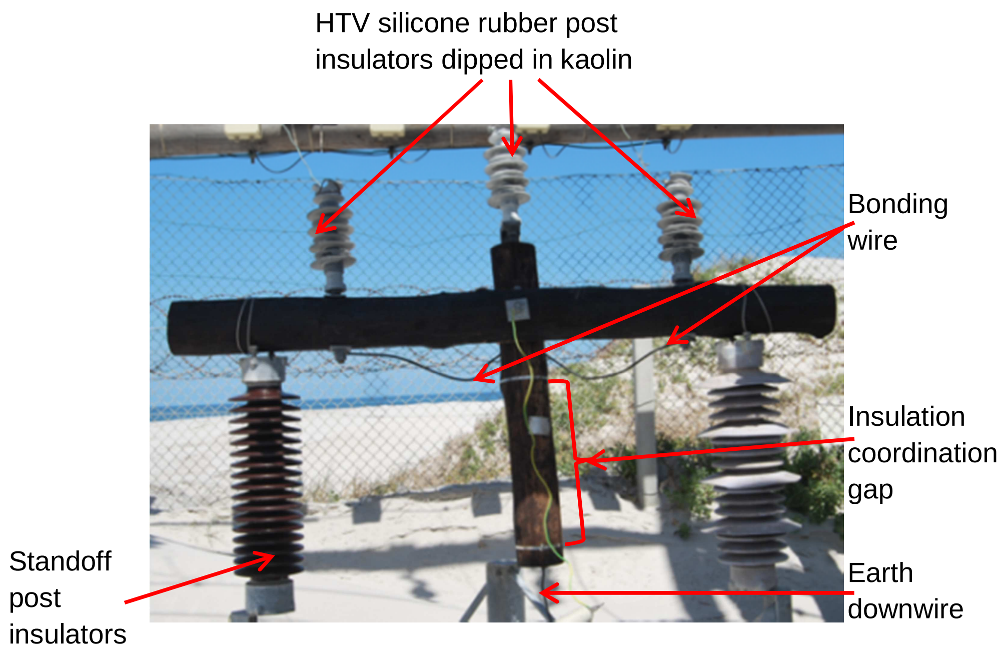


Figure 3.16: Insulator profile evaluation with only HTV silicone rubber post insulators

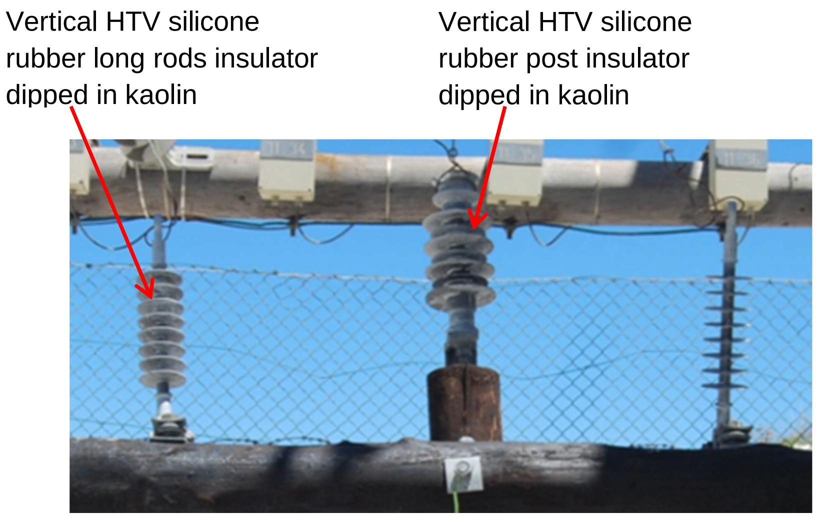


Figure 3.17: Insulator profile evaluation with HTV silicone rubber post and long rods insulators (same structure setup as Figure 3.16, two insulators changed to HTV silicone rubber long rods)

All the measurements on the structure were conducted at KIPTS for the two cases. Sea water was sprayed to pollute the insulators and the structure for a set of measurements. Thereafter salt solution was sprayed as a pollutant for the concluding measurements.

The HTV silicone rubber post insulators were selected for the investigation because the HTV silicone rubber insulators are easily available in various shapes and can be manufactured in any desired form.

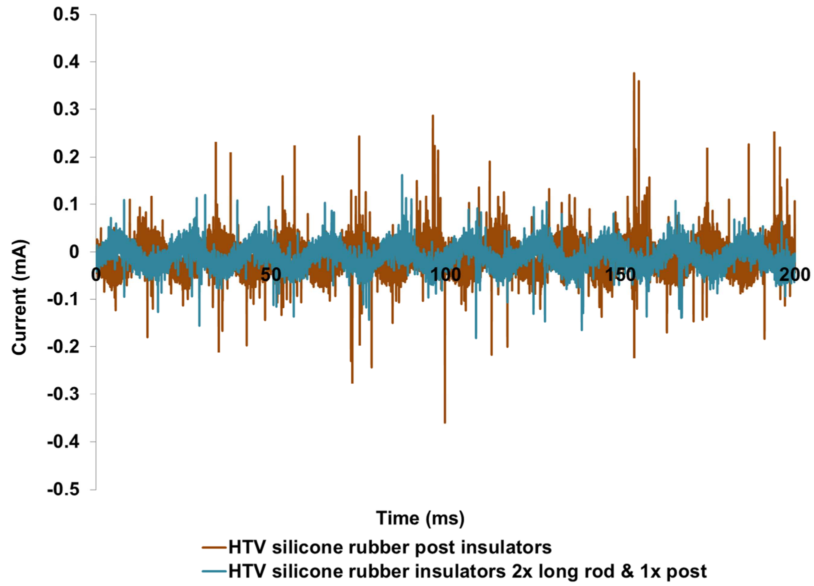
Results

Table 3.3 has details of the conditions under which the measurements were taken. The weather information shown is fairly comparable with the exception of humidity that has a 4% difference. The slightly high humidity is therefore expected to manifest in spikes for the time domain waveforms.

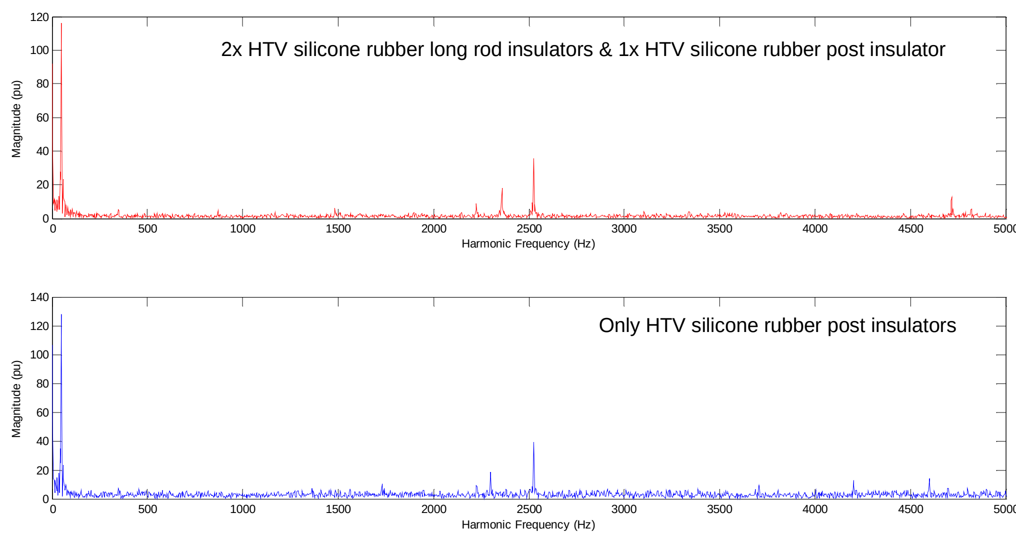
Table 3.3: Conditions under which measurements were taken for investigating the effect of insulator profile

Case investigated	Temperature (^oC)	Humidity (%)	Wind speed (m/s)	Pollution applied	Surface condition before testing
Structure with all vertical 2X HTV silicone rubber long rod and 1X post	20.7	75	4.9	Sprayed on sea water (salinity of 40 kg/m^3) for first set	Insulators cleaned with water and dipped in kaolin solution
Structure with all vertical HTV silicone rubber post	20.1	79	4.4	Sprayed on salt solution (salinity of 112 kg/m^3) for last set	

Figures 3.18, 3.19, 3.20, 3.21 and 3.22 show the measured leakage current waveforms and the corresponding spectra.



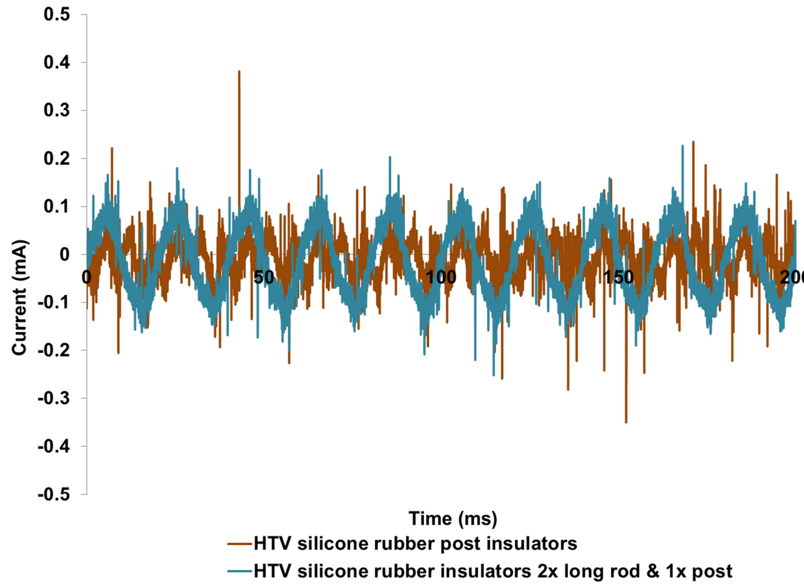
a)



b)

Figure 3.18: Insulator profile evaluation, structure dry and dry insulators: a) Time domain, b) Frequency domain

Figure 3.18 shows the total r.m.s. leakage current was 0.039 mA for the case of all post insulators and 0.026 mA for the case of two long rod insulators.



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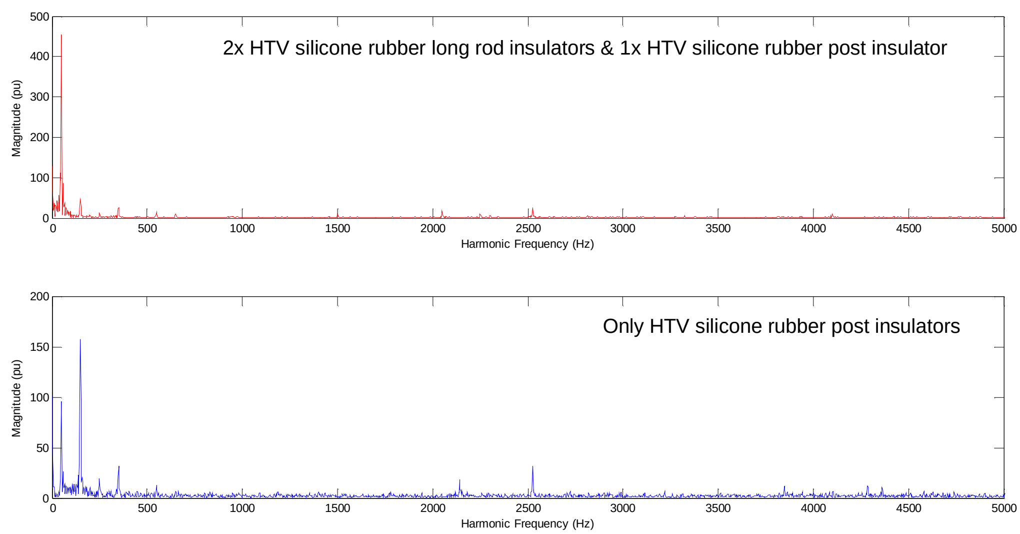
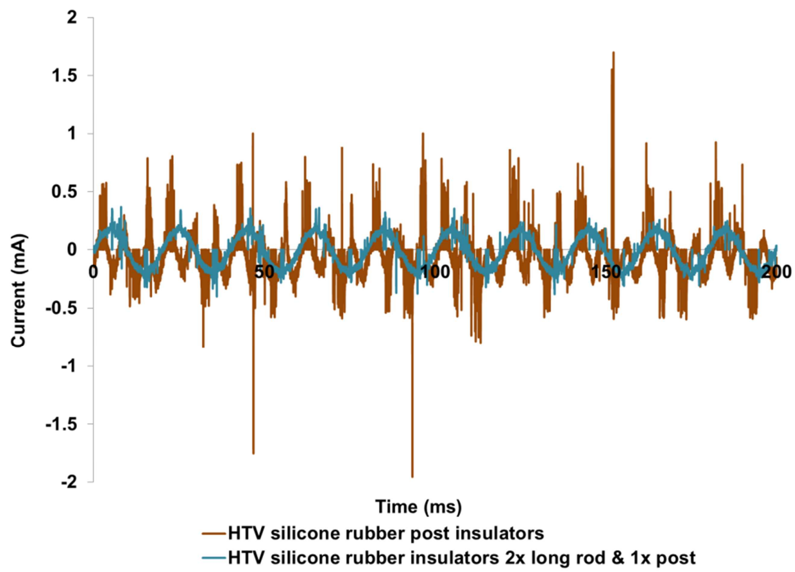


b)

Figure 3.19: Insulator profile evaluation, structure sprayed with sea water (salinity of 40 kg/m^3): a) Time domain, b) Frequency domain

Figure 3.19 shows the total r.m.s. leakage current was 0.073 mA for the case with two silicone rubber long rod insulators and 0.038 mA for the case with all silicone rubber post insulators. The structure experienced arcing activity for the case with only silicone rubber post insulators as shown by the presence of higher frequency components in the spectrum waveform.



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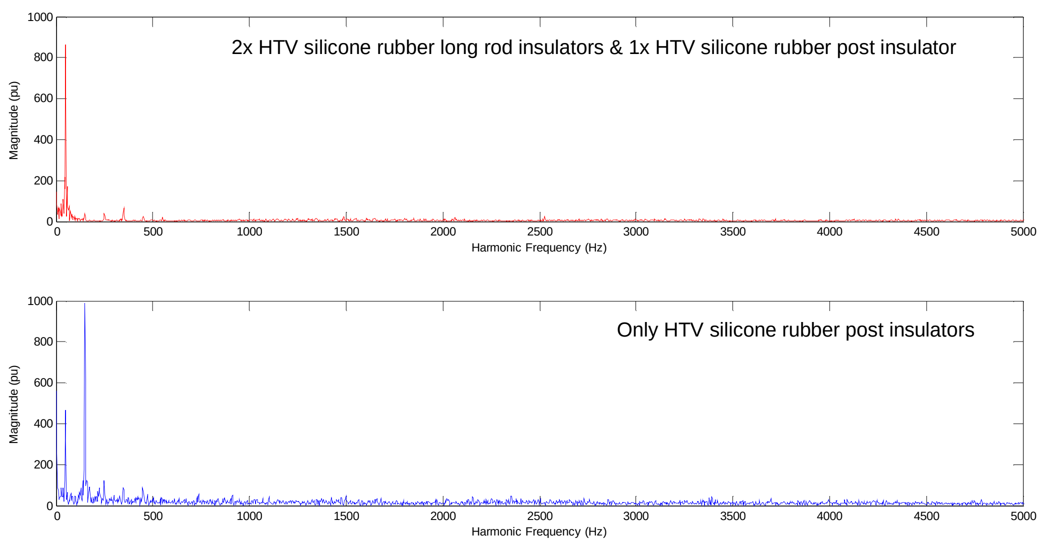
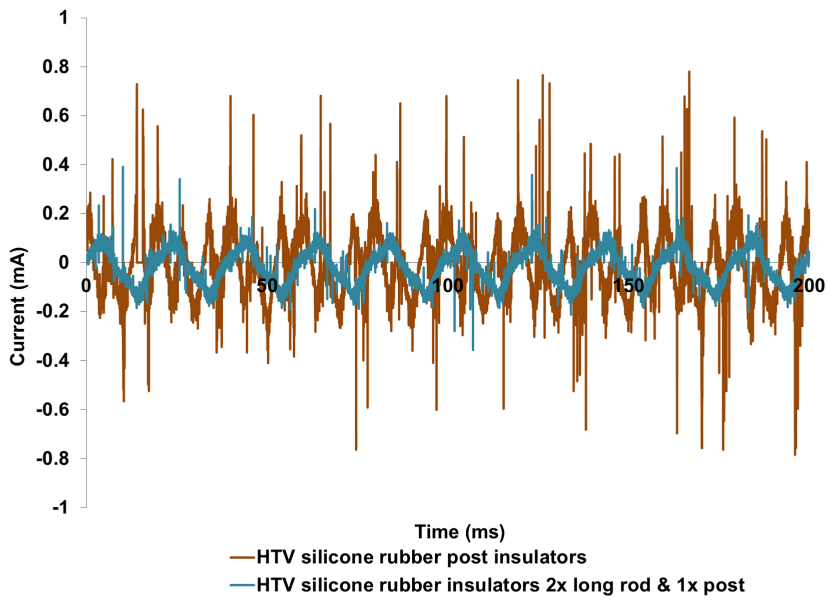


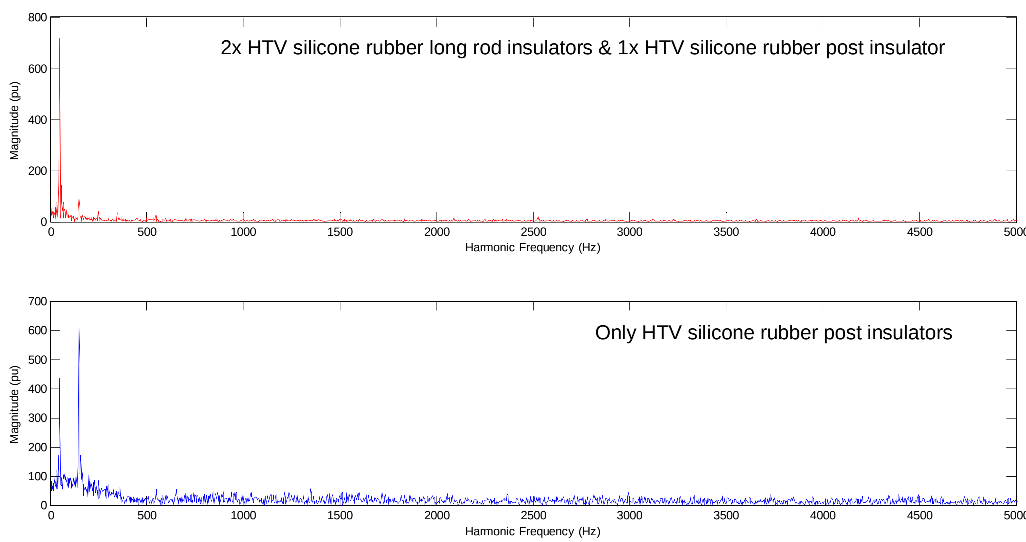
b)

Figure 3.20: Insulator profile evaluation, structure re-sprayed with sea water (salinity of 40 kg/m^3): a) Time domain, b) Frequency domain

The re-spray measurements shown in Figure 3.20 illustrate a total r.m.s. leakage current of 0.139 mA for the two silicone rubber long rod insulators and 0.206 mA for the case with all silicone rubber post insulators implying that for the latter case the structure experienced a greater heating effect.



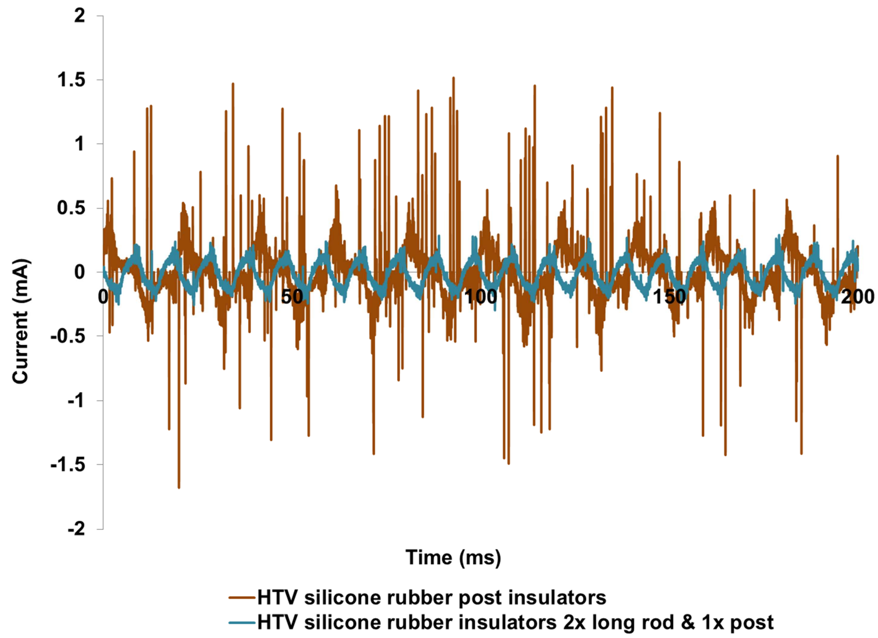
a)



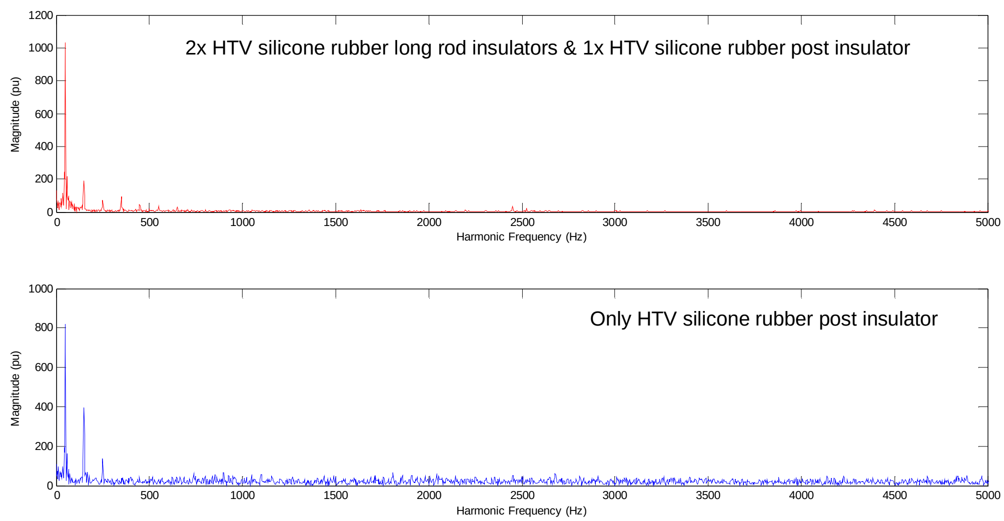
b)

Figure 3.21: Insulator profile evaluation, structure sprayed with salt solution (salinity of 112 kg/m^3): a) Time domain, b) Frequency domain

Figure 3.21 shows that total r.m.s. leakage current was 0.075 mA for the case of all two long rod insulators compared to 0.173 mA for the case with all silicone post insulators.



a)



b)

Figure 3.22: Insulator profile effect evaluation, structure re-sprayed with salt solution (salinity of 112 kg/m^3): a) Time domain, b) Frequency domain

Figure 3.22 shows a total r.m.s. leakage current of 0.167 mA for the case with two silicone long rod insulators and 0.233 mA for the case with all silicone post insulators. Still after re-spraying the case with all silicone posts exhibited noticeable arcing activity.

Summary of outcomes

The structure leakage current magnitude for the case with two silicone long rod insulators was the lowest for most of the pollution incidents.

3.4 Neutral Voltage at the Insulation Coordination Gap

A comparison between the voltage at the insulation coordination gap and the three-phase supply voltages was performed to establish the behaviour of the voltage at the gap to observe if there is a neutral shift. It was projected that phase insulators will not conduct the same due to the variation of the surface pollution layer on them and that the imbalance will cause an increase of the neutral voltage resulting in a neutral shift at the wood gap metal bandit strip and the earth inside the woodpole. This is of interest because Ross in [2] indicated that a large voltage between adjacent dry wood (high resistance) and wet wood (low resistance) will result in electrical breakdown across some parts of the dry wood should those parts be short enough. Persadh in [5] also stated that voltage gradients at the interface between metal fittings and wood can be high enough to cause local discharges that lead to current activity and if prolonged enough will ultimately ignite the wood.

The concern with neutral shift is that the rise in neutral voltage can result in a large voltage between the metal bandit strap at the insulation coordination gap and the earth of the dry wood inside the pole which if sustained for a long period may lead to charring or burning from within the pole at the insulation coordination gap.

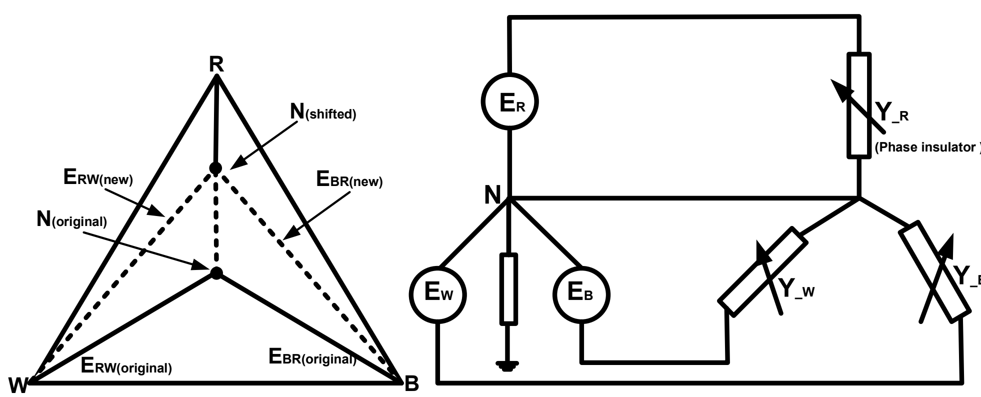


Figure 3.23: Neutral shift phasor diagram and structure model

The phasor diagram and model illustrating neutral shift is shown in Figure 3.23. It demonstrates that for a three phase system with balanced load the neutral voltage with respect to the system’s earth is expected to be equal to zero. However should the load impedance vary the same system will have a neutral voltage and the neutral point will shift from its origin. To illustrate this, Figure 3.24

a), b) and c) respectively show waveforms of a simple R-C circuit model that includes wood for three cases where load impedance difference was 1 Ω and then increased to 1 kΩ and finally 1 MΩ. It is shown in Figure 3.24 that as the imbalance between the load impedances increases so does the value of the neutral voltage that has shifted from the origin.

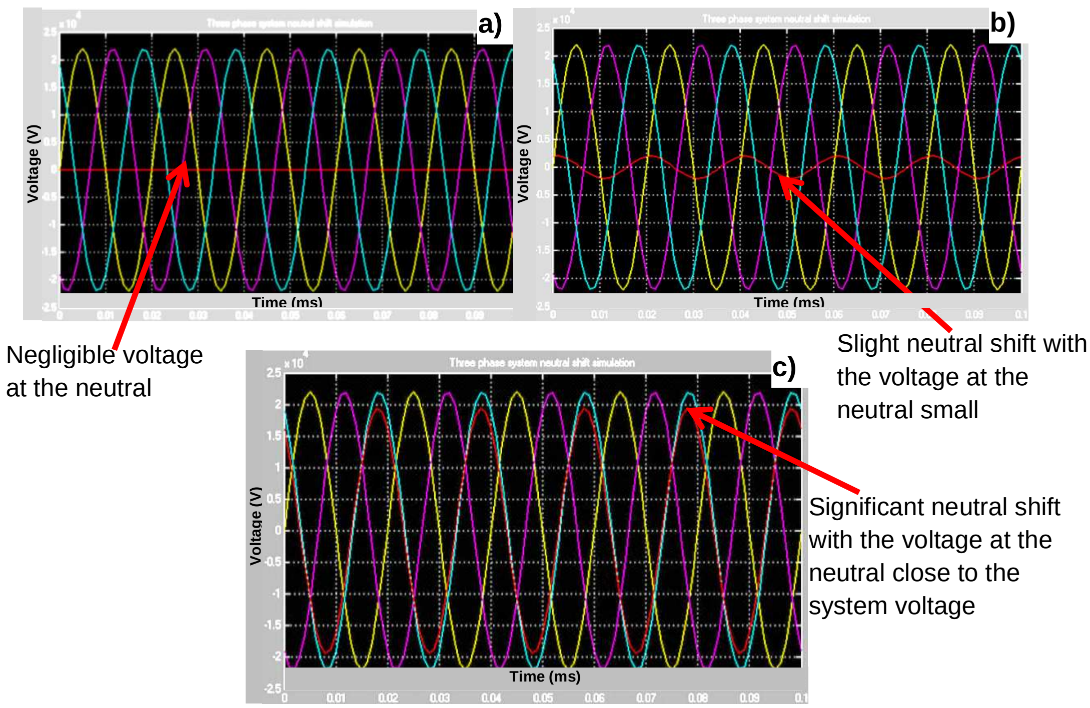


Figure 3.24: Neutral shift demonstration for a) small load imbalance (1 Ω difference), b) intermediate load imbalance (1 kΩ difference), c) large load imbalance (1 MΩ difference)

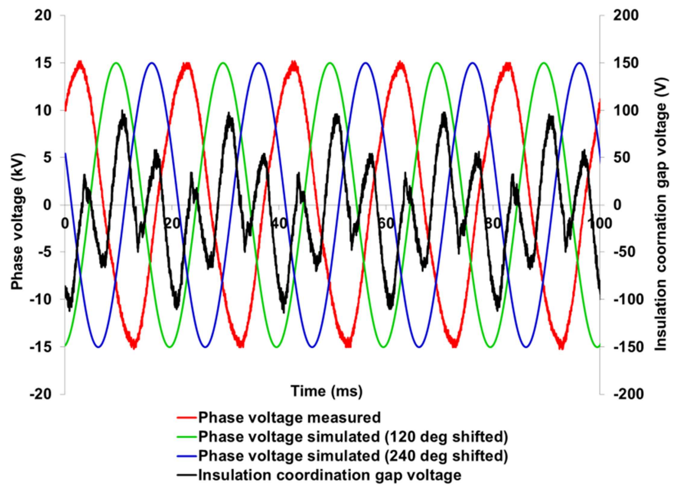


Figure 3.25: Neutral shift for structure with 2x horizontal porcelain insulators: supply voltages vs. structure's gap voltage

The measurement results shown in Figure 3.25 are for the condition when the structure and phase insulators were sprayed with salt solution (salinity of 10 kg/m^3). Figure 3.25 shows the insulation coordination gap voltage (approximately 0.05 kV) to be a 50 Hz waveform with a 3rd harmonic. This implies that there was resistive current due to conductive pollution on the structure and phase insulator. The neutral voltage value suggests that the imbalance due to pollution on the phase insulators was not large.

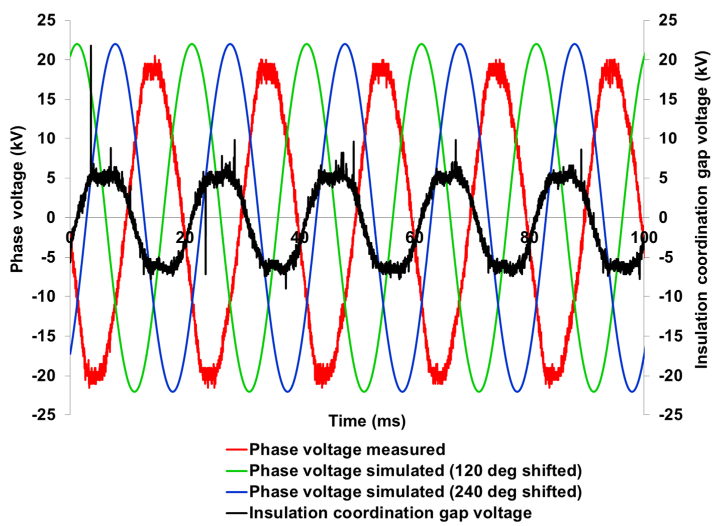


Figure 3.26: Neutral shift evaluation for structure with only vertical porcelain insulators: supply voltages vs. structure's gap voltage

Figure 3.26 displays measurement results for the condition when the structure and phase insulators were sprayed with salt solution (salinity of 112 kg/m^3). The neutral voltage at the gap has shifted and has an r.m.s. value of 4.72 kV. It is conjectured that the neutral shift is caused by intermediate imbalance of the leakage currents of the phase insulators. The voltage has the potential to cause voltage gradients at the bandit strap and adjacent dry wood area of the pole which if sustained for long may result in internal wood burning at the insulation coordination gap.

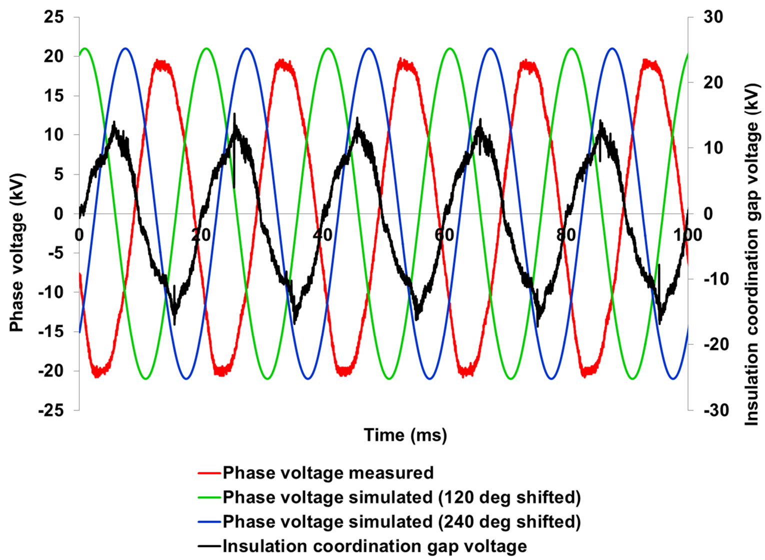


Figure 3.27: Neutral shift evaluation for structure with 2X HTV silicone rubber long rod insulators: supply voltages vs. structure's gap voltage

Figure 3.27 shows measurement results for the condition when the structure and phase insulators were sprayed with a salt solution (salinity of 112 kg/m$^{3)}$. The structure's neutral voltage shifted as a result of a large imbalance of the leakage currents at the phase insulators. The neutral shift observed has an r.m.s. voltage of 8.89 kV.

3.4.1 Summary of Findings

The following observations were made:

- The neutral shift at the insulation coordination gap is observed for all the structure cases evaluated.
- This phenomenon is as a result of imbalance of the leakage currents of the phase insulators. The greater the imbalance the larger the voltage at the insulation coordination gap and the higher is the risk of wood burning from the inside due to sustained and concentrated voltage gradients leading to discharges and current activity.

3.5 Summary

Leakage current performance of a scaled down woodpole structure for various insulator application cases was presented. Leakage current was evaluated from measurements obtained from testing the scaled down structure in an outdoor "live chamber". The results may be summarised as follows:

- The effect of insulator orientation on structure leakage current performance was evaluated from comparing the case with all porcelain post insulators in a vertical position to the case with one vertical insulator and two horizontal insulators. The latter case resulted in lower leakage current than the former. The outcome is similar to the expectations from literature [10] and [15]. Insulator orientation for porcelain post insulators is perceived to have a noteworthy effect on the structure leakage current. An average leakage current magnitude difference of approximately 24% was observed for the cases investigated.
- The effect of insulator material was investigated for the structure configuration with all vertical post insulators. Porcelain and HTV silicone rubber insulators were compared. Leakage current magnitude for the case with silicone rubber insulators was lower, and in agreement with expectations raised in literature [10] and [12]. The average difference in leakage current magnitude was approximately 62% for the compared cases. It is to be noted that the results are for insulators that were both post type but with dissimilar shed profile. Nonetheless, the outcomes form a good basis that effect of insulator material on leakage current performance of a woodpole structure is substantial and can be verified in the subsequent section from full scale test measurements that used insulators with the same profile.

  The effect of insulator profile for HTV silicone rubber insulators was investigated from the case with all vertical post insulators and the case with one post and two long rods all positioned vertically. The case with all vertical post insulators experienced sporadic tracking activity leading to a greater heating effect. Weather conditions may have had some influence on the heating, arc and tracking activity on the structure. Taking that in consideration, the case with one post and two long rods all positioned vertically exhibited lower leakage current magnitudes compared to the case with all vertical post insulators. An average leakage current magnitude difference of approximately 38% was observed. The outcome differs with [17] by El-Hag et al. It was anticipated that a silicone rubber insulator with a shape comprising a large shed diameter and short shed inter-spacing, resembling the post insulator, would exhibits low levels of leakage current. The outcome can be substantiated in the next section from measurements on full scale woodpole structures.

- From all the above results, the leakage current performance of a complete structure may be improved by changing certain application of the insulators and by the choice of insulator material and shape. These measures together with certain bonding arrangements may reduce the risk of pole-top fires.

- The structure voltage across the insulation coordination gap, was measured for all of the above cases. It was found that a neutral shift exists for all cases and the value of the voltage across the insulation coordination gap increases with increased imbalance of the phase insulators leakage currents. More work is required where a detailed model for the energised structure and insulators is developed and simulated.

4 MEASUREMENTS ON FULL SCALE WOODPOLE STRUCTURES

Leakage current measurements on full scale woodpole structures for a period of one year are presented. The structures were exposed to natural coast pollution. The objective was to determine the structure leakage current performance from field conditions and to substantiate outcomes from laboratory measurements on reduced scale woodpole structure.

4.1 Pole-Top Fires Research at KIPTS

Several woodpole distribution structures at KIPTS were built for an ongoing Eskom's pole-top fires research project. The objective of the project was to understand the mechanism and mitigation of pole-top fires. The layout of the woodpole structures construction is shown in Figure 4.1.

The structures were built at KIPTS because the site has conditions conducive for high leakage currents. KIPTS is approximately 50 m from the sea. It has marine, industrial and agricultural pollution from nearby companies and farms [4, 12]. The other reason KIPTS was the most suitable site was that it had a three-phase supply and facilities to log leakage current measurements in a safe and reliable manner.

4.2 Woodpole Structures Selected for Measurements

Four woodpole structures were identified to be suitable for evaluating structure leakage current performance. The selection considered the structure cross-arm configuration and the type of insulators used.

The structures selected were,

1. Structure-1: partially bonded through an insulation coordination gap, comprising a wood cross-arm with porcelain post insulators all mounted vertically.
2. Structure-2: partially bonded through an insulation coordination gap, comprising a wood cross-arm with RTV silicone rubber coated porcelain insulators all mounted vertically.
3. Structure-3: fully bonded through a continuous earth downwire, comprising steel T-frame cross-arm with HTV silicone rubber insulators (one post and two long rods).
4. Structure-4: partially bonded through an insulation coordination gap, comprising steel A-frame cross-arm with porcelain insulators (centre phase insulator mounted vertically and outer phase insulators mounted horizontally).

All the woodpole structures and accessories on them were constructed according to Eskom's norm. Insulators used are of the same specification as the insulators used on the reduced scale woodpole structures. Their specification can therefore be found in Appendix B.

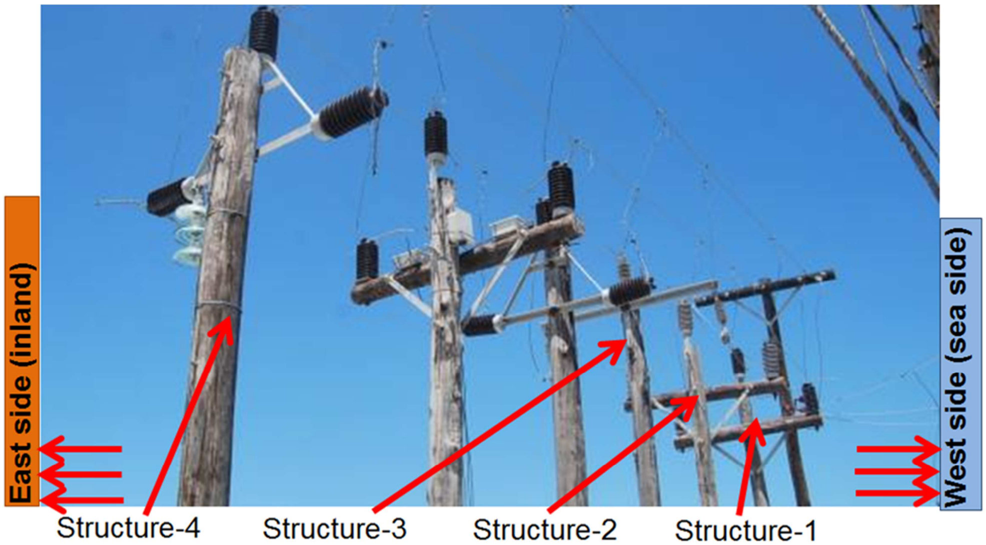


Figure 4.1: Setup of full scale woodpole structures at KIPTS

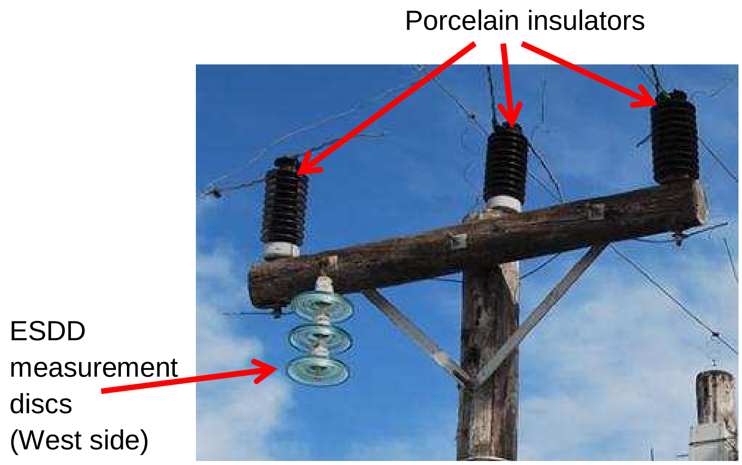


Figure 4.2: Structure-1 used for insulator orientation evaluation and insulator material evaluation [3]

Structure-1 shown in Figure 4.2 was the first structure from the sea side of the test station and had its insulation coordination gap facing the sea. It had glass disc insulators for pollution monitoring. Logged leakage current from this structure were studied to determine the effect that insulator material and insulator orientation have on the structure leakage current performance.

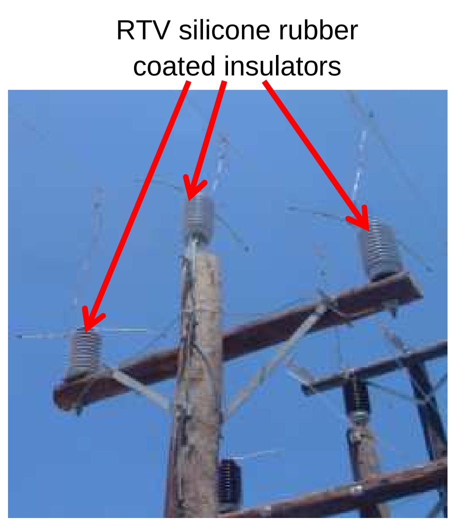


Figure 4.3: Structure-2 used for insulator material evaluation and insulator profile evaluation [3]

Figure 4.3 shows Structure-2. It was the second structure from the sea side. It had its insulation coordination gap facing away from the sea. Leakage current data logged from this structure was used to evaluate the effect of insulator material by comparing it with data from Structure-1.

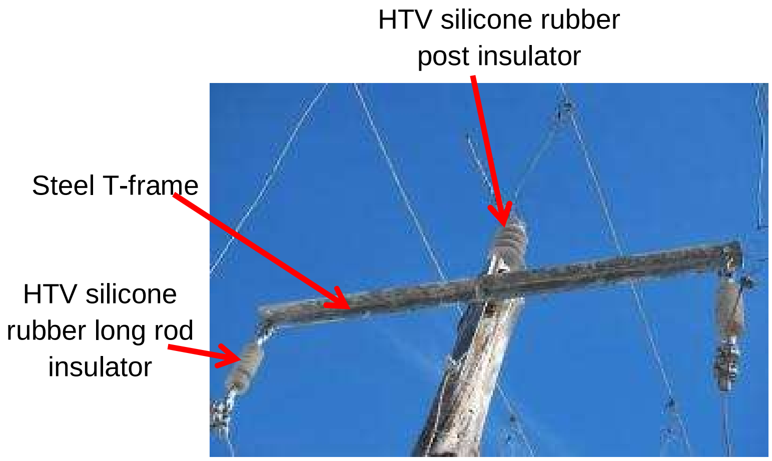


Figure 4.4: Structure-3 used for insulator profile evaluation [3]

Structure-3 is shown in Figure 4.4. Its leakage current data was compared to Structure-1 to evaluate effect of insulator material. It was further compared to Structure-2 to establish the effect of insulator profile.

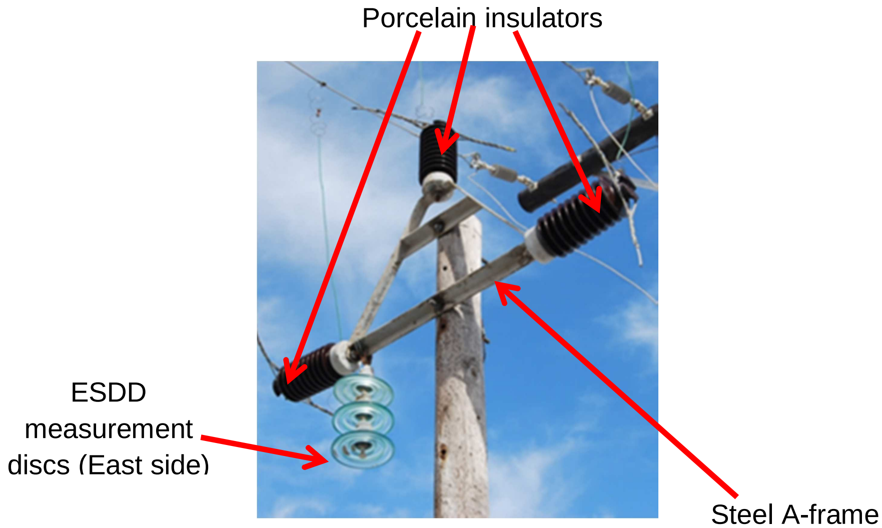


Figure 4.5: Structure-4 used for insulator orientation evaluation [3]

Figure 4.5 shows Structure-4. Its insulation coordination gap was facing east away from the sea. Leakage current logged from the structure was used to evaluate effect of insulator orientation by comparing it to that obtained from Structure-1.

4.3 Measurement Method and Setup

Leakage current was logged using the KIPTS logger system, On-line Leakage Current Analyser (OLCA). Figure 4.6 illustrates a typical structure with the measurement setup.

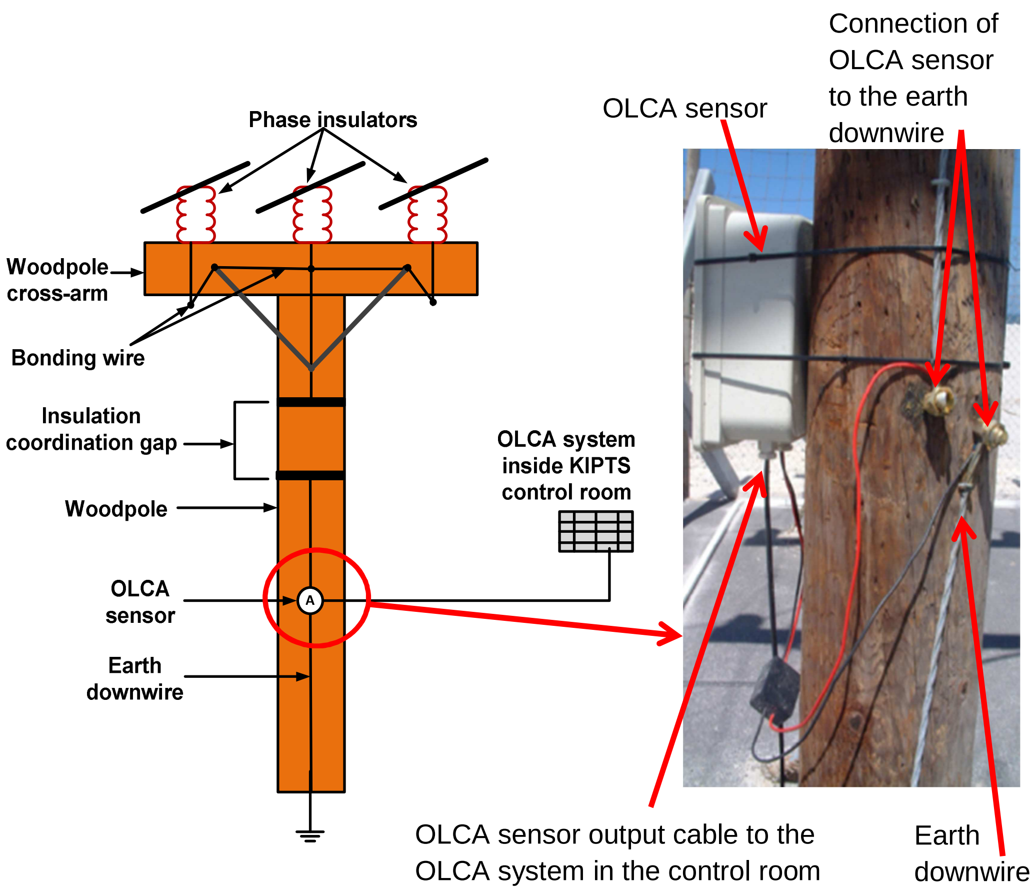


Figure 4.6: Typical layout measurement setup on a full scale woodpole distribution structure [3]

Leakage current measurements were taken with a galvanically isolated current sensor that sampled at 2 kHz. It used bin counting and stored values every 10 minutes. The output cable of the sensor was connected to the OLCA control system located inside the KIPTS control room. The OLCA system was able capture peak currents, r.m.s. currents as well as weather parameters (from the weather station connected to it). Further details regarding the OLCA logger system are found in Vosloo [12 p.43, p.123-125].

Pollution was measured from measurement of the Equivalent Salt Deposit Density (ESDD) on glass discs mounted on Structure-1 and on Structure-4. The ESDD value was measured according to SANS 60815-1.

Daylight visual inspections on the structures were conducted utilising a digital camera. Night visual inspections were conducted when conditions with relative humidity above 70% were present. A corona camera was utilised for night inspections. Metal and wood interfaces between phase insulators and wood cross-arm were of particular interest as well as the insulation coordination gap because tracking usually occurs at those regions.

A three-phase 22 kV (phase-phase) supply was used to energise the test structures. The structures were energised continuously unless a fault occurred on the station or when the station was switched off for maintenance. Each phase insulator was connected to a live conductor through a fuse to minimise the risk of tripping the entire test facility in a case of a flashover.

4.4 Measurement Results

4.4.1 Logged leakage current for a year

Pollution severity is used in interpreting leakage current results. Figure 4.7 shows pollution measured at KIPTS for a year. It is shown that KIPTS experienced heavy pollution during the summer period. Moreover the month of November had the highest recorded heavy pollution. Structure-1 on the west side (closest to the sea) recorded very heavy pollution levels of 0.71 mg/cm^2 and Structure-4 on the east side (inland, furthest from the sea) registered 0.79 mg/cm^2.

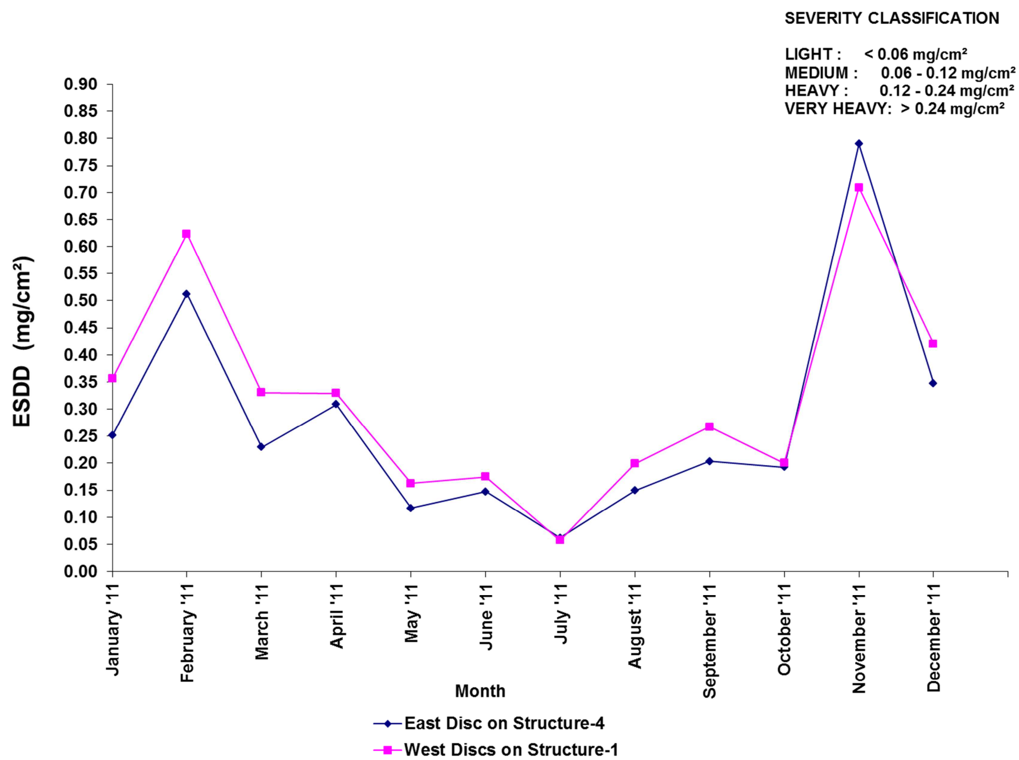


Figure 4.7: KIPTS ESDD record for a year

Insulator orientation effect

To investigate effect of insulator orientation, Structure-1 leakage current was compared to that of Structure-4.

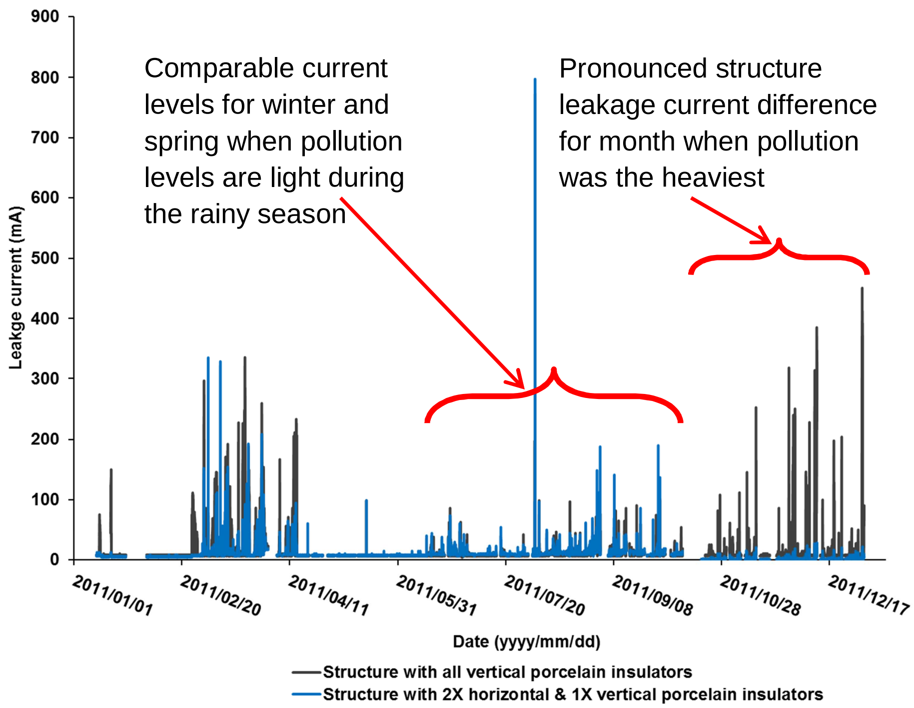


Figure 4.8: Year leakage current measurements for evaluating effect of insulator orientation

Figure 4.8 shows that during a dry spell with very heavy pollution, Structure-1 (with all the porcelain insulators mounted vertically) had high leakage current compared to the Structure-4 (with two horizontal insulators). Pole-top fires often occur after a dry spell when insulators have accumulated significant pollution and are exposed to light wetting.

Insulator material effect

Effect of insulator material was investigated using logged leakage current comparison between Structure-1 and Structure-2 logged leakage current. Further comparison was done between Structure-1 Structure-3.

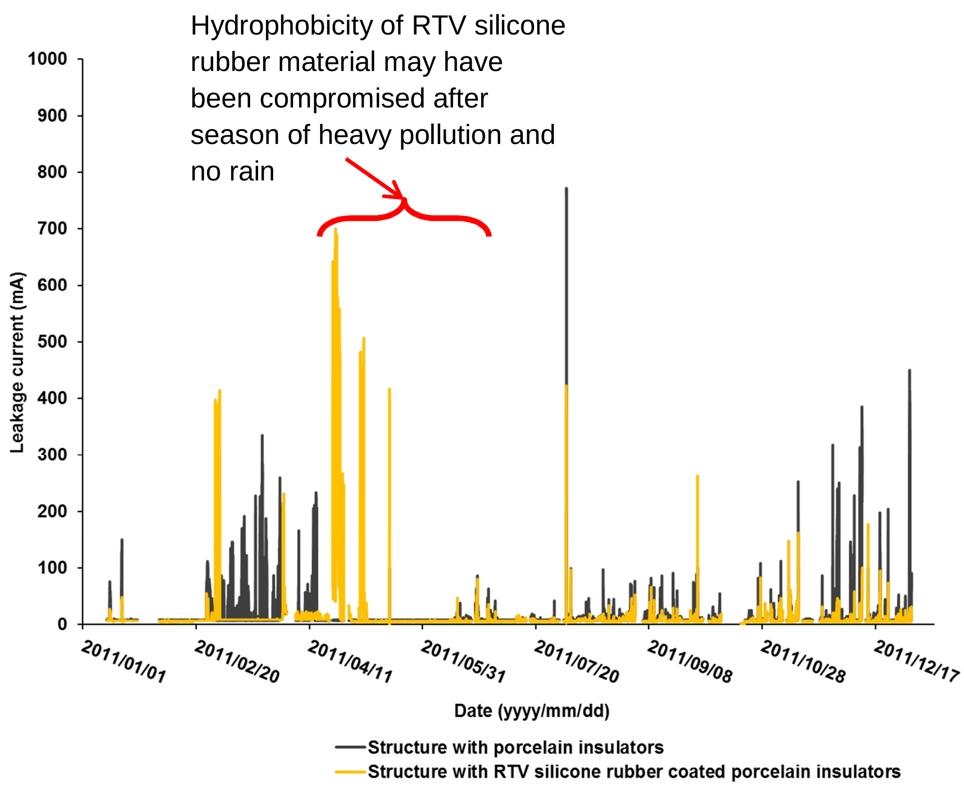


Figure 4.9: Year leakage current measurements for evaluating effect of insulator material (porcelain vs. RTV silicone rubber coating)

Figure 4.9 shows that Structure-1 with porcelain insulators logged high leakage current for most of the year. Structure-2 with RTV silicone rubber coated insulators showed high leakage current levels in April. This occurred at the end of summer which is a dry long spell with very heavy pollution. It is probable that the RTV silicone rubber insulator material temporarily had its hydrophobicity compromised due to accumulation of very heavy pollution. The material recovered after winter and a significant leakage current difference is observed at the end of the year.

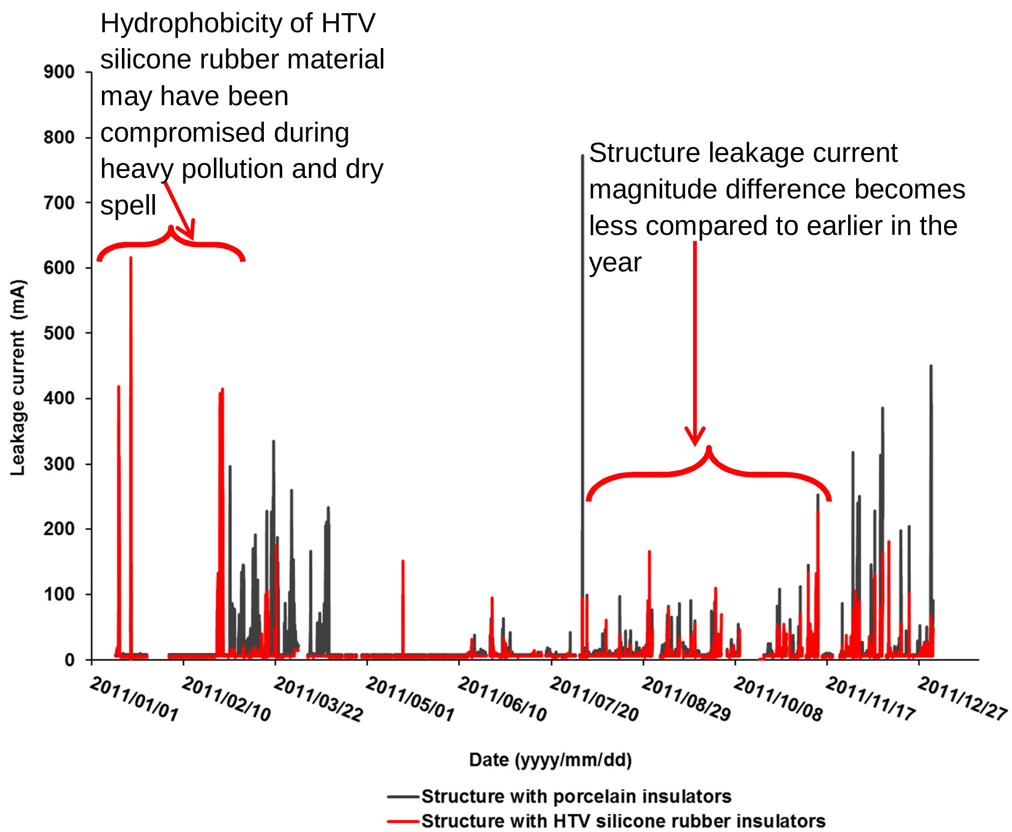


Figure 4.10: Year leakage current measurements for evaluating effect of insulator material (porcelain vs. HTV silicone rubber)

Figure 4.10 shows that Structure-3 (with HTV silicone rubber insulators) recorded low leakage current for most of the year compared to Structure-1 (with porcelain insulators). It was noticed that the leakage current difference between the two structures reduced as the year progressed compared to earlier in the year. This may be due to the quality of additives or fillers used in the silicone material.

Insulator profile effect

To investigate effect of insulator profile, logged leakage current of Structure-2 with post RTV silicone rubber coated insulators was compared to that of Structure-3 with one post and two long rod HTV silicone rubber insulators with an acknowledgement that the silicone rubber material preparation and manufacturing varies.

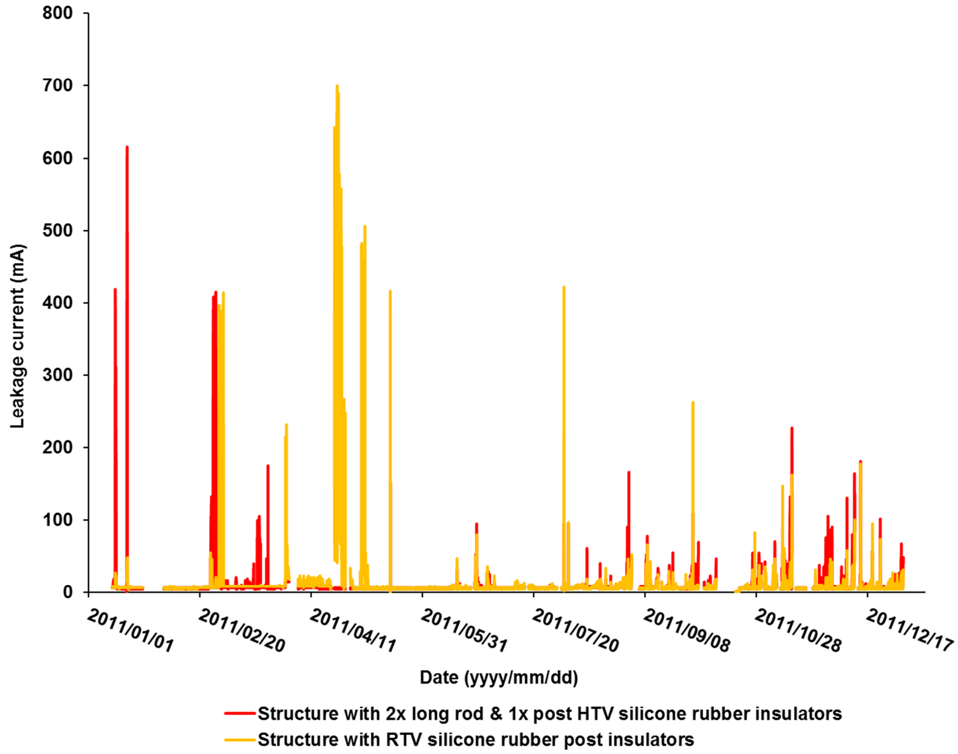


Figure 4.11: Year leakage current measurements for evaluating effect of insulator profile

Figure 4.11 shows that Structure-2 (with RTV silicone rubber coated insulators) recorded less leakage current level for most parts of the year when compared to Structure-3 (with HTV silicone rubber insulators). It is illustrated that insulators that are short and wide can improved leakage current performance of woodpole structures.

4.4.2 Logged leakage current for a day

Pole-top fires are most likely to occur after a dry period of heavy pollution [4,5]. It was reported by Vosloo in [12] that during the summer season KIPTS has very heavy pollution and no rain. He also stated that humidity levels at KIPTS are typically high during the night after 8 pm. High humidity levels are synonymous with critical wetting leading to pollution conduction and the flow of leakage current. Therefore worst conditions that are likely to lead to pole-top fires are present at KIPTS during summer nights.

Presented results are for the day when the site experienced the heaviest pollution level and also when humidity was high. The last day of November is presented because Figure 4.1 showed November as the month with the heaviest pollution.

Insulator orientation effect

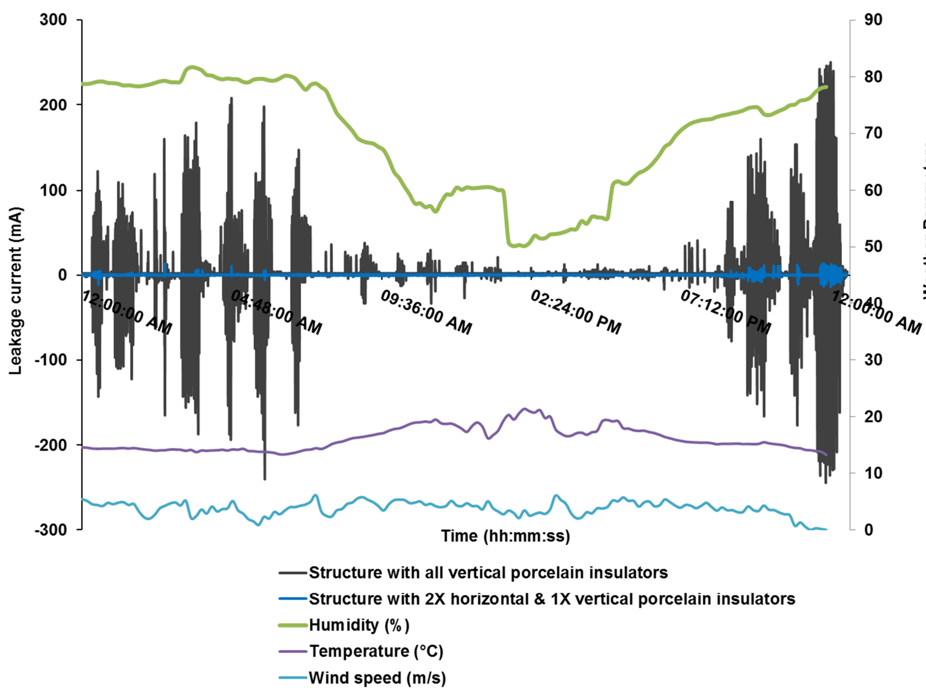
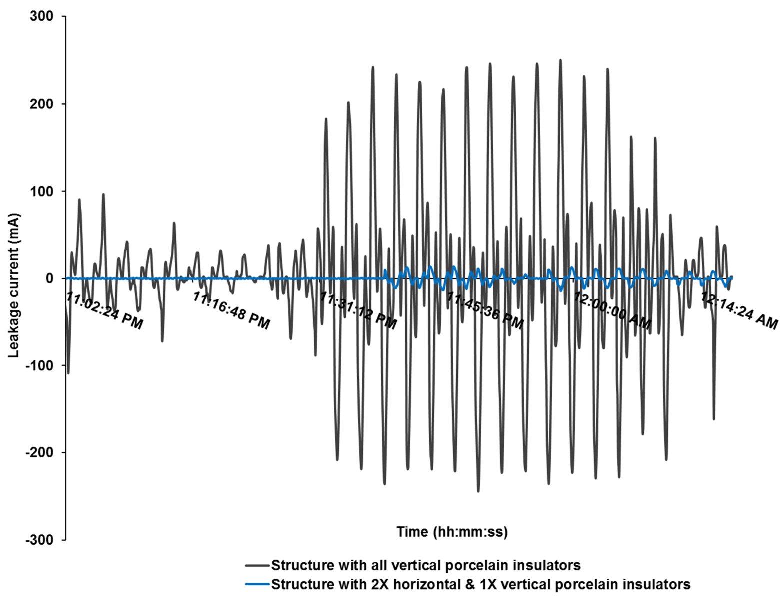


Figure 4.12: Day leakage current measurement for evaluating effect of insulator orientation

Figure 4.12 shows leakage current waveform comparisons between Structure-1 (with all insulators mounted vertically) and Structure-4 (with two insulators mounted horizontally). It can be observed that Structure-4 exhibited very low levels of leakage current compared to Structure-1. It is worth noting that Structure-4 was exposed to heavier pollution compared Structure-1. Furthermore the logged leakage current pattern varied as expected when compared to the humidity and temperature levels. As humidity increased and temperatures dropped, the logged current increased.



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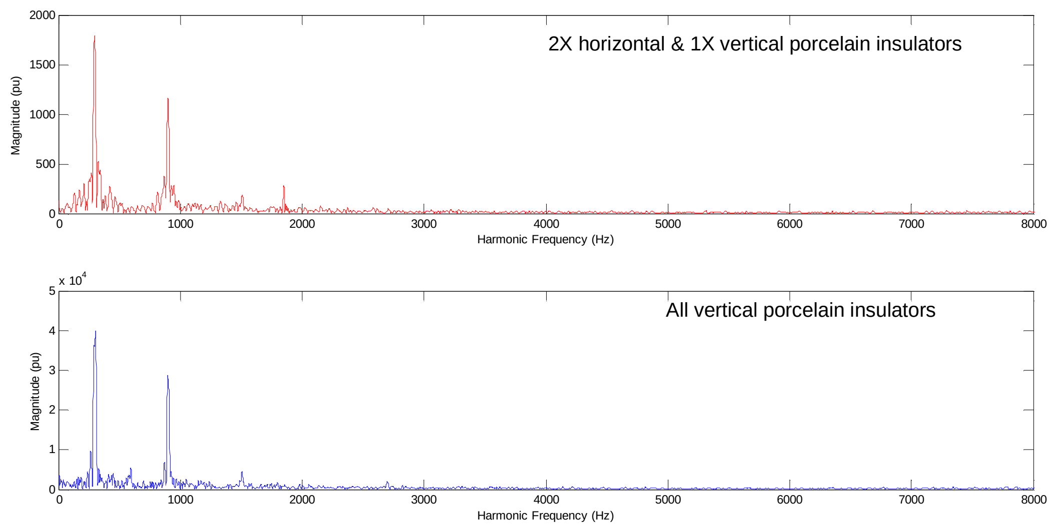


b)

Figure 4.13: Late night leakage current measurement for evaluating effect of insulator orientation a) current waveform, b) current spectrum

Figure 4.13 a) and b) show zoomed in leakage current results from Figure 4.12 when humidity was high. Current levels reached approximately 250 mA on Structure-1 (with all porcelain insulators mounted vertical) compared to the

Structure-4 (with two insulators mounted horizontally) that recorded current levels of approximately 10 mA.

Insulator material effect

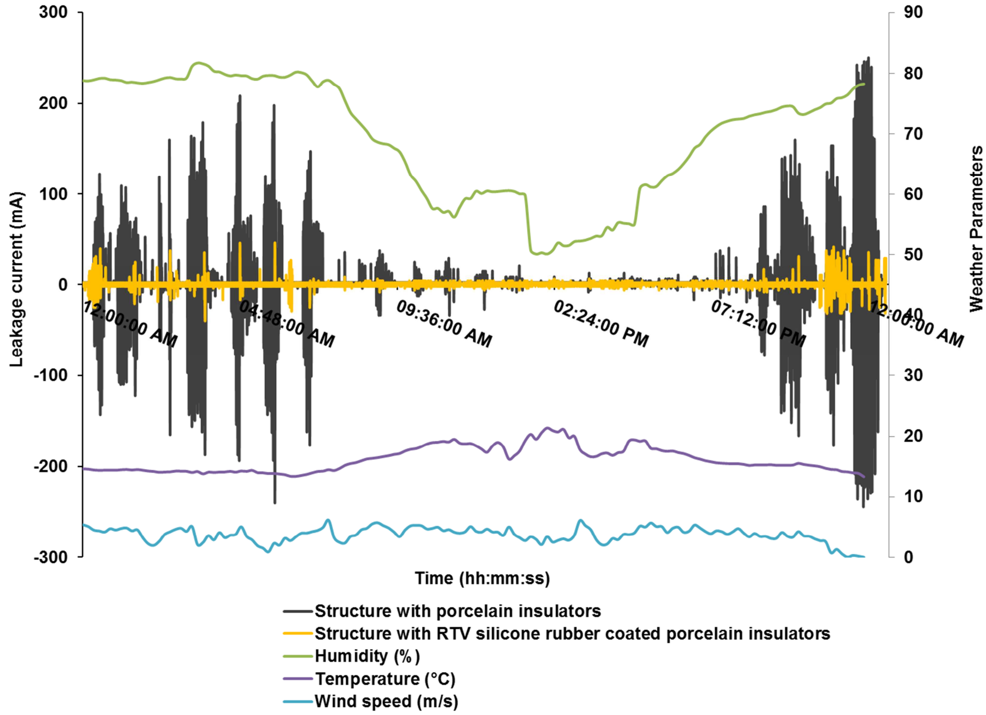


Figure 4.14: Day leakage current measurements for evaluating effect of insulator material (porcelain vs. RTV silicone rubber)

It is observed from Figure 4.14 that through the day Structure-1 with porcelain insulators logged high leakage current compared to Structure-2 with RTV silicone rubber coated porcelain insulators. The current waveform trend followed the humidity trend as expected.

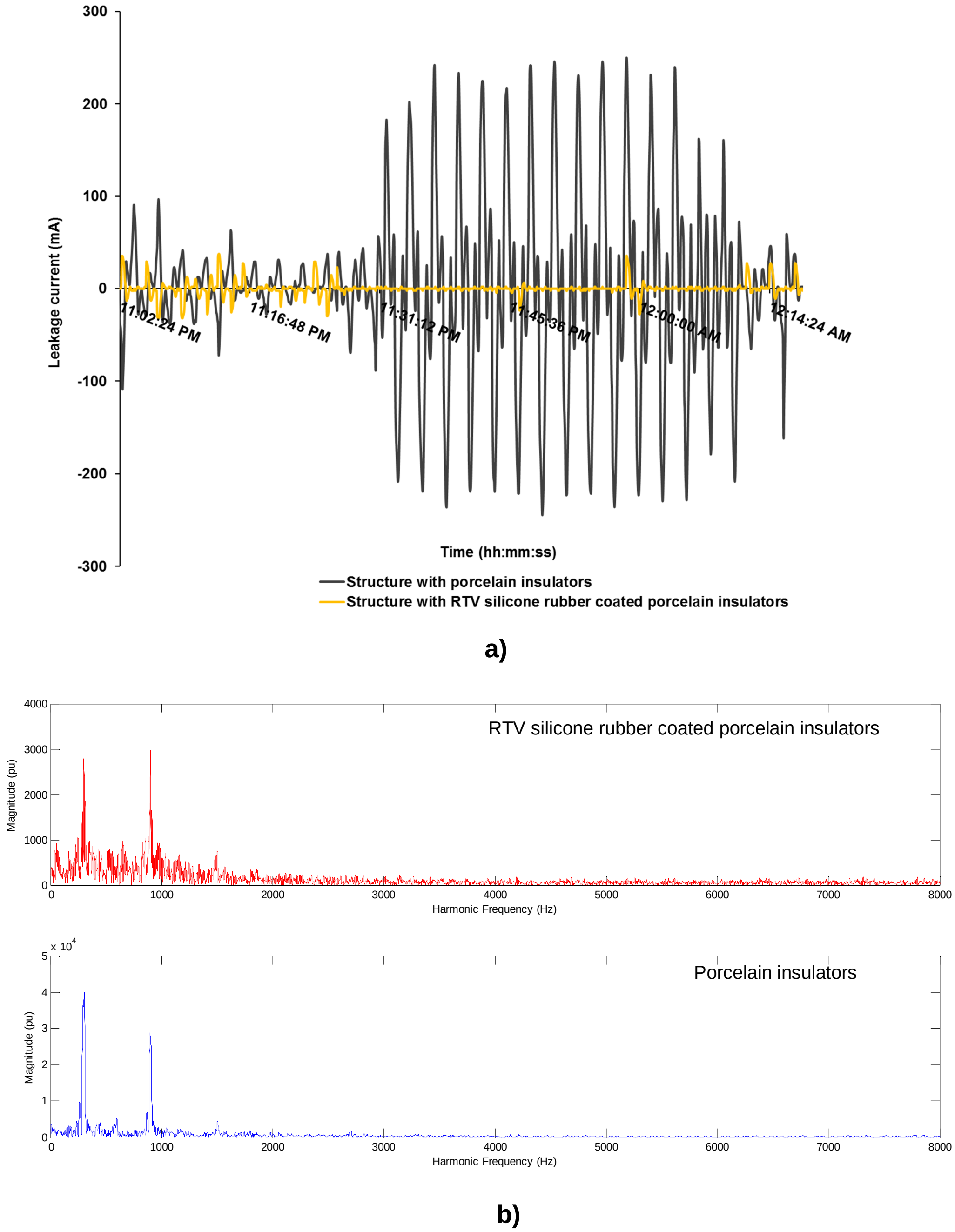


Figure 4.15: Late night leakage current measurement for evaluating effect of insulator material (porcelain vs. RTV silicone rubber), a) current waveform, b) current spectrum

Figure 4.15 a) and b) show zoomed in leakage current results from Figure 4.14. It shows that logged leakage current reached approximately 250 mA and 35 mA respectively for Structure-1 and Structure-2.

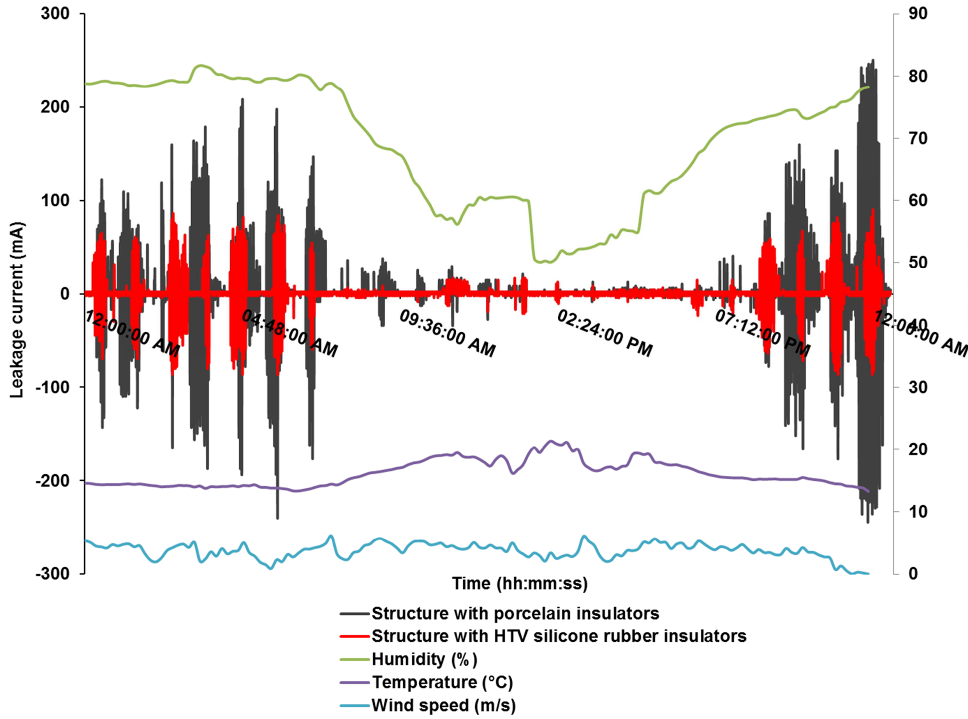
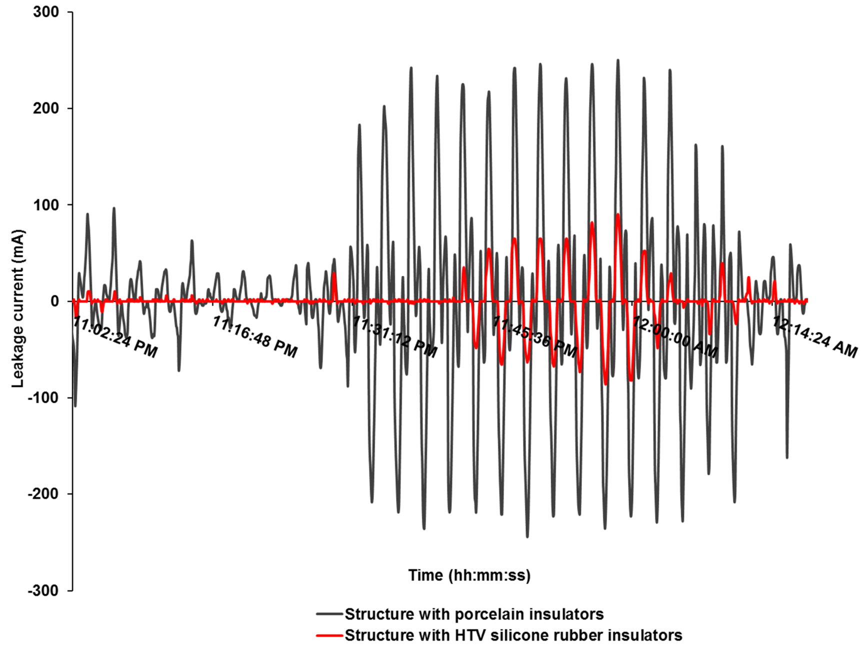
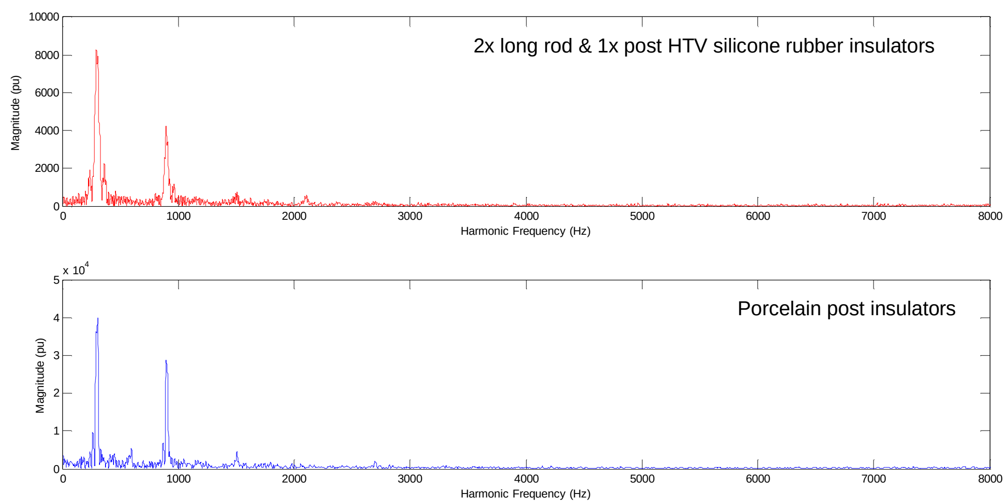


Figure 4.16: Day leakage current measurement for evaluating effect of insulator material (porcelain vs. HTV silicone rubber)

Figure 4.16 shows that leakage current increased and decreased as humidity increased and temperature decreased. Leakage current was low for Structure-3 with HTV silicone rubber insulators compared to Structure-1 with porcelain insulators. The results are as anticipated from general insulator material testing knowledge from individual insulator testing.



a)



b)

Figure 4.17: Late night leakage current measurement for evaluating effect of insulator material (porcelain vs. HTV silicone rubber), a) current waveform, b) current spectrum

Figure 4.17 a) shows that leakage current for Structure-3 with HTV silicone rubber insulators reached approximately 80 mA and reached 250 mA for Structure-1 with porcelain insulators. Figure 4.17 b) shows the spectrum of the measured leakage current. The 3rd harmonic content shows that the structures are susceptible to arcing and possibly burning from tracking.

Insulator profile effect

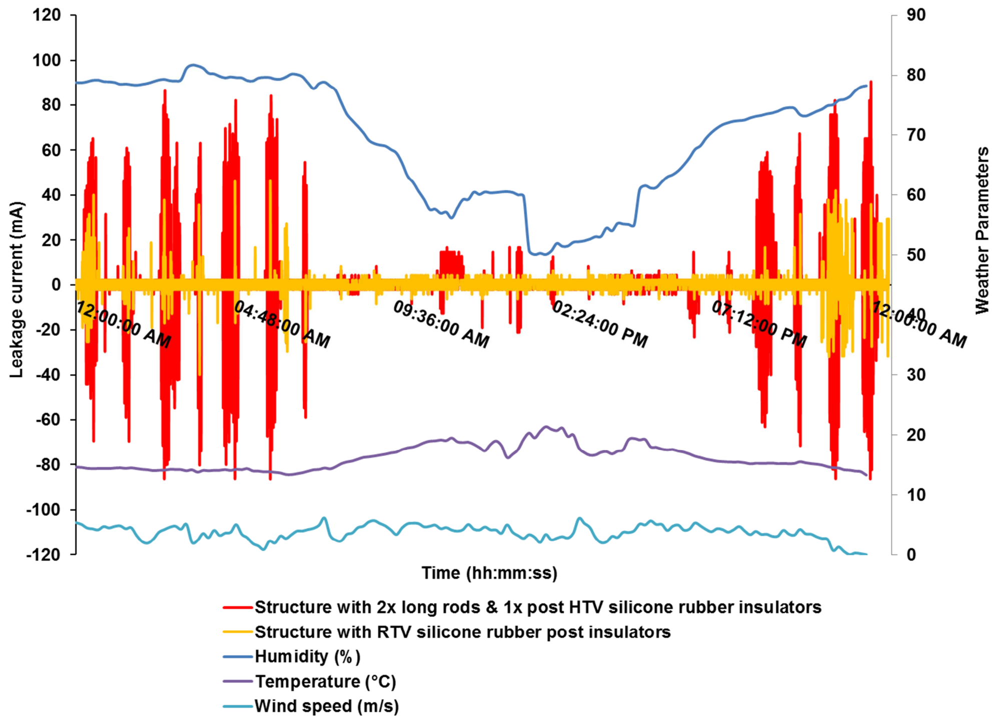
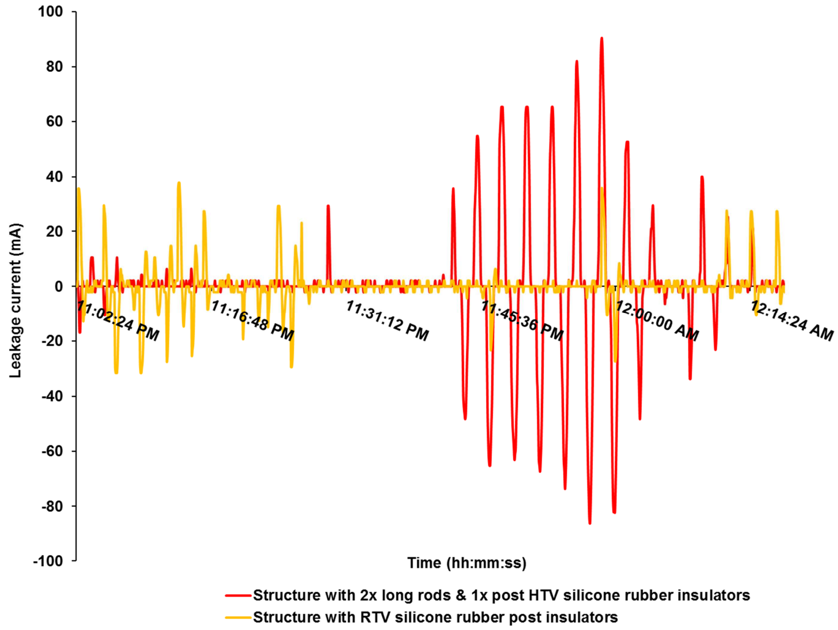
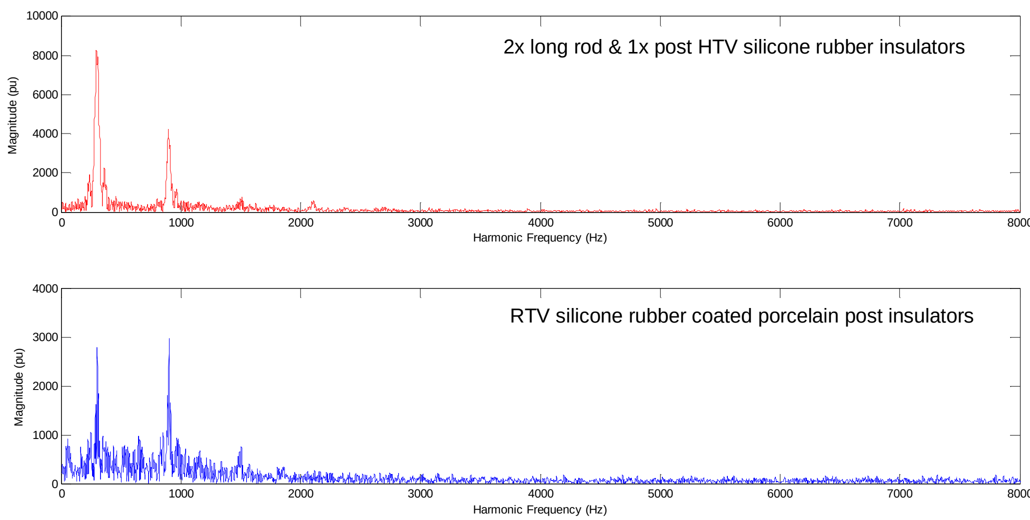


Figure 4.18: Day leakage current waveform for evaluating effect of insulator profile

Figure 4.18 shows that Structure-2 with only post silicone rubber insulators recorded low leakage current throughout the day compared to Structure-3 which had two long rod insulators. The better Structure-2 leakage current performance can be attributed to the use of insulators with a profile comprising a wide and short profile.



a)



b)

Figure 4.19: Late night leakage current measurement for evaluating effect of insulator profile, a) current waveform, b) current spectrum

Zoomed in leakage current results of Figure 4.18 are shown in Figure 4.19 a) and b). Structure-2 with post insulators recorded low leakage current levels approximately 35 mA compared to Structure-3 leakage current levels of approximately 80 mA when humidity was at its highest for the day. The results demonstrate that insulators that have wide shed diameter and short shed to shed spacing contribute to improved structure leakage current performance. This is in agreement with findings in El-Hag et al in [17].

4.5 Visual Inspections

Visual inspections on structures conducted during daylight and night are presented. The objective of the inspections was to observe signs of tracking or charring on woodpole structures. Tracking or scorching on a woodpole indicates a compromised structure leakage current performance and high risk of pole-top fires.

4.5.1 Daylight inspections

Daylight visual inspections were performed using a digital camera looking for arcing damage and tracking. It is known that metal and woodpole interface points are most susceptible to tracking due to voltage gradient and where pole-top fires typically initiate [2, 6, 8, 9]. Inspections were made at metal and wood interfaces on the woodpole structure to ascertain if there were indications of external tracking or burning. Insulator spindle connection to the wood cross-arm, steel cross-arm connection to the vertical woodpole, and insulation coordination gap were therefore observed and close range pictures of them taken during inspections. Since Structure-3 was fully bonded with a continuous earth downwire and did not have an insulation coordination gap, only the steel cross-arm interface to the vertical woodpole was inspected.

Cross-arm inspections

Figure 4.20: Daylight inspection on wood cross-arm

Figure 4.20 shows photographs of the wood cross-arm interface with the insulator spindle. No evidence of tracking was observed on the wood cross-arm. None of the inspected structures with wood cross-arms showed signs of charring or had the presence of carbon.

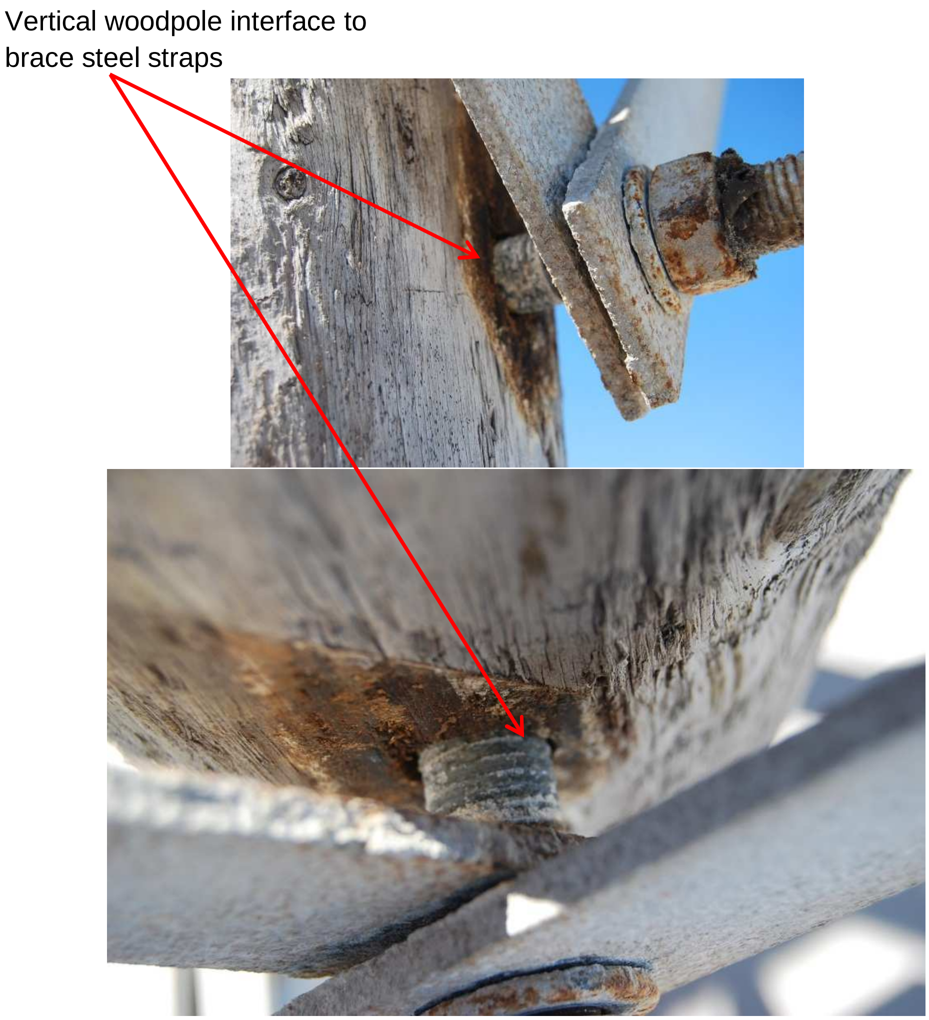


Figure 4.21: Daylight inspection on vertical woodpole interface with brace strap

A photograph of the point where the brace strap supporting the wood cross-arm comes into contact with the vertical woodpole is shown in Figure 4.21. There was no sign of tracking observed at the contact point. The dark brown or black marks observed were from the creosote woodpole treatment. None of the inspected structures with brace straps connecting the wood cross-arm to the vertical woodpole exhibited tracking marks.

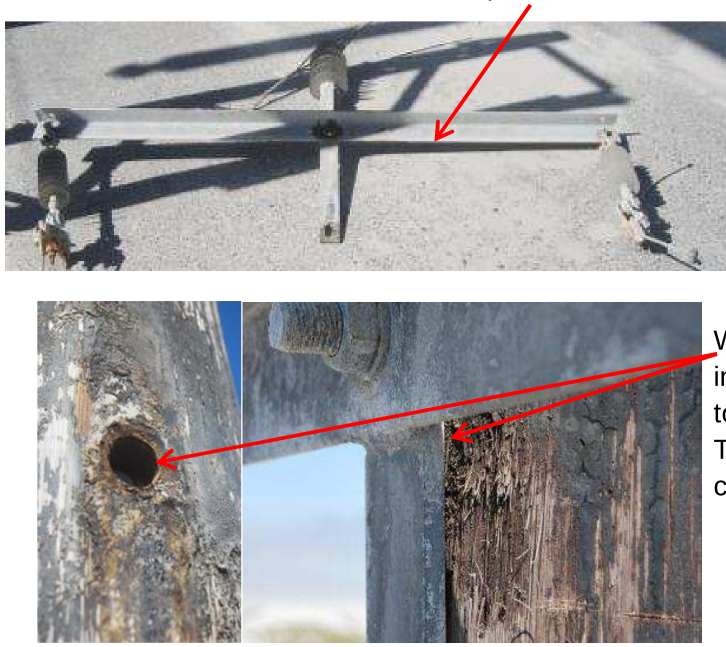


Figure 4.22: Daylight inspection on steel T-frame cross-arm interface with vertical woodpole

Figure 4.22 shows photographs at the point where the steel T-frame cross-arm comes into contact with the vertical woodpole. The structure did not have any signs of tracking at the interface point. Observed black marks are from the creosote used to treat the pole.

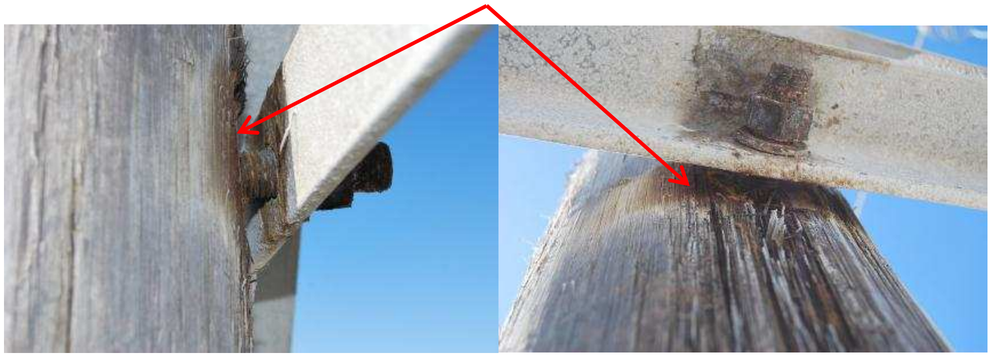


Figure 4.23: Day time inspection on steel A-frame cross-arm interface with vertical woodpole

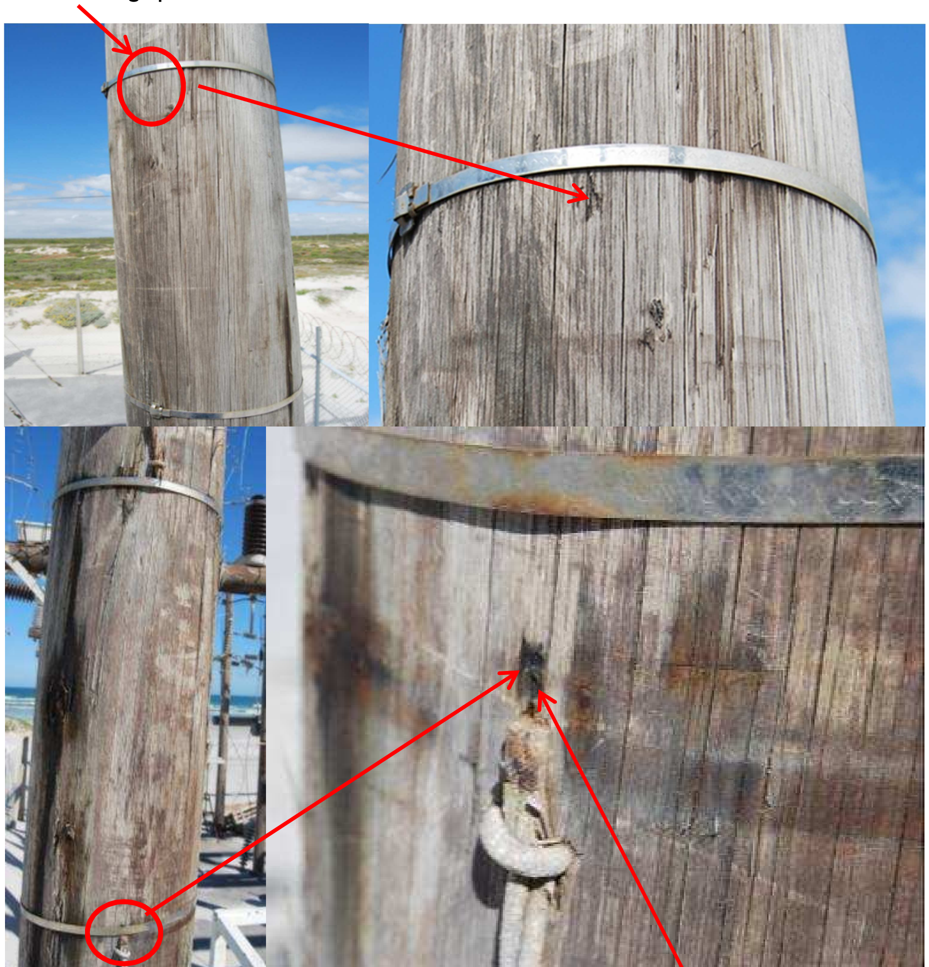
Photographs of Structure-4 at the interface of the steel A-frame with the vertical woodpole are shown in Figure 4.23. No signs of tracking were observed at the interface.

Insulation coordination gap inspections

Figure 4.24: Daylight inspection of insulation coordination gap on Structure-2 with woodpole cross-arm and RTV silicone rubber coated insulators

Figure 4.24 shows tracking signs and smouldering marks on Structure-2 at the bandit strap inside the insulation coordination gap. There is a risk of pole-top fires for this structure.

Tracking mark at the top bandit strap of the insulation coordination gap



Smoldering mark at the end of the earth downwire at the bottom of the insulation coordination gap

Figure 4.25: Daylight inspection of insulation coordination gap on Structure-4 with A-frame steel cross-arm, one vertical and two horizontal porcelain insulators

Figure 4.25 show that Structure-4 had burning marks at the bandit strap and at the tip of the earth downwire after the insulation coordination gap. The risk of pole-top fires exists for this type of structure arrangement.

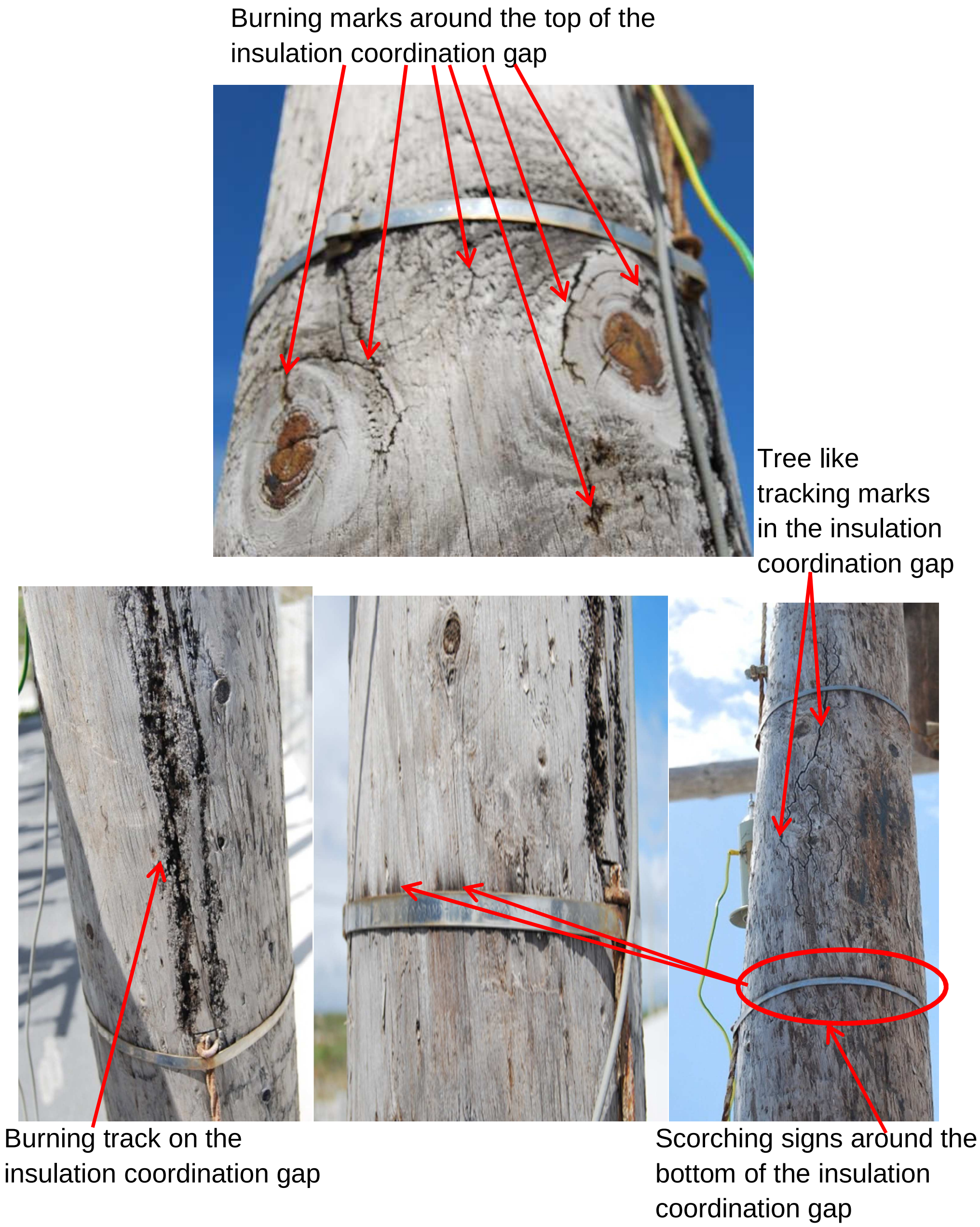


Figure 4.26: Daylight inspection of the insulation coordination gap on Structure-1 with woodpole cross-arm and all vertical porcelain insulators

Figure 4.26 shows severe tracking and deep burning marks at the insulation coordination gap of Structure-1. Deep burning marks on the gap are on the west side facing the sea and the tree-like tracking marks on the gap are on the southern side. The structure's pronounced burning marks are attributed to its immediacy to sea spray. There is a high risk of pole-top fires for Structure-1 compared to Structure-2 and Structure-4.

4.5.2 Night inspections

The aim of night visual inspection was to detect tracking activity that may not necessarily be visible during daylight and had not left tracking marks. A corona camera was used for capturing the visuals. Inspections were performed on the wood cross-arm, phase insulators and the insulation coordination gap.

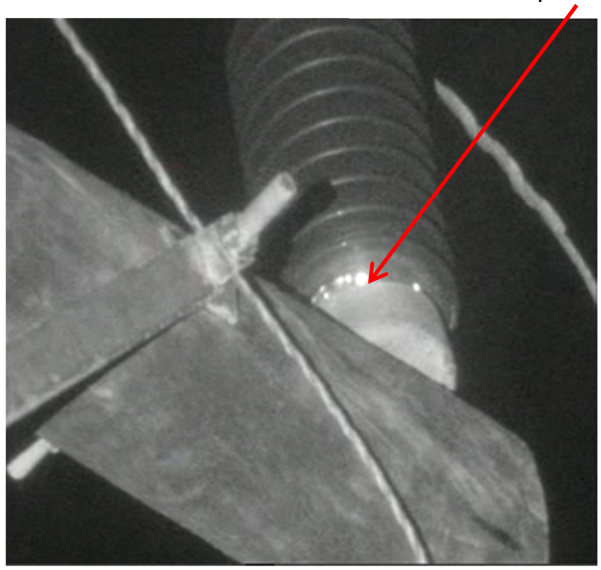


Figure 4.27: Night inspection of cross-arm on Structure-1 with wood cross-arm and all vertical porcelain insulators

Figure 4.27 shows tracking observed at the top of the phase insulator metal base. No activity was observed at the bottom of the insulator base or on the wood cross-arm. The results agree with daylight findings of no presence of indications of external tracking or burning on the cross-arm or on the spindle and wood interface.

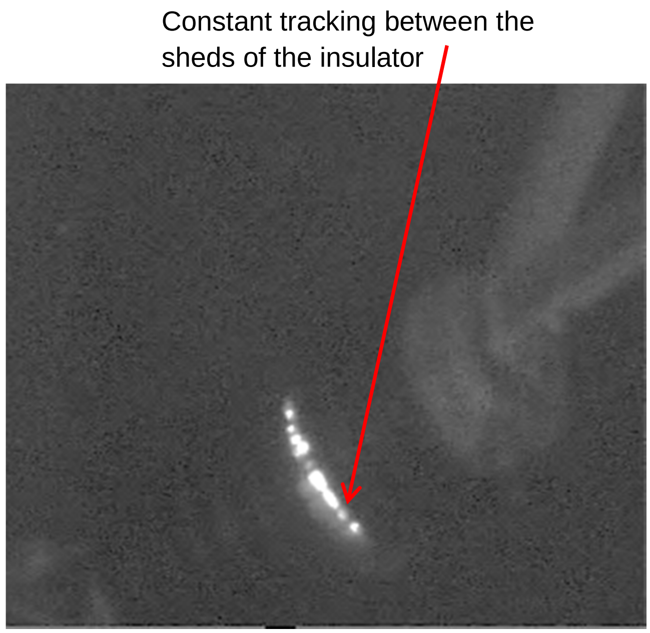


Figure 4.28: Night inspection on Structure-4 with steel A-frame cross-arm, one vertical and two horizontal porcelain insulators

Figure 4.28 shows that constant tracking activity was observed on the insulator sheds of the porcelain insulators on the steel A-frame. The activity did not lead to tracking at the contact point between the steel cross-arm and vertical woodpole. From daylight inspections no signs of tracking or scorching were observed at that interface either.

Figure 4.29: Night inspection of cross-arm on Structure-2 with wood cross-arm and RTV silicone rubber coated insulators

No visible activity was observed for the structure with silicone rubber coated insulators as shown in Figure 4.29.

Figure 4.30: Night inspection of insulation coordination gap on Structure-1 with wood cross-arm and all vertical porcelain insulators

Figure 4.30 shows tracking within the insulation coordination gap of Structure-1. The tracking was observed to be sporadic and at times constant. This finding concurs with daylight inspections where burning marks were observed on the structure. No tracking was captured for other structures with insulation coordination gaps during the time of night inspection.

4.6 Discussion

The effect of insulator orientation was investigated by comparing the downwire leakage current logged on Structure-1 and Structure-4. The structure with two horizontally-mounted insulators (Structure-4) recorded generally lower levels of leakage current. The reason for this is expected because insulators mounted horizontally will have a larger surface area exposed and accessible for effective washing by rain and removal of solid pollution particles by wind than the same insulator mounted vertically [10, 15]. In addition, horizontal orientation inhibits accumulation of pollution particles because the particles are able to fall freely though the insulator sheds. Hence, Structure-4 recorded low magnitudes of leakage current for most parts of the year except during the rainy season with light pollution where the leakage current performance of the two structures was similar.

Structure-2 with RTV silicone rubber coated insulators had better leakage current performance (lower leakage current magnitudes) than Structure-1 with uncoated porcelain insulators. This is explained by the fact that silicone rubber insulator material is hydrophobic and prevents critical wetting of the polluted surface and restricts conduction of leakage current [2]. The results are in agreement with findings from the reduced scale test measurements. Structure-2 recorded low leakage current when the hydrophobicity is still retained or has recovered. It was observed that Structure-2 recorded noticeably high leakage current towards the end of a dry spell during very heavy pollution and for this reason more work is required to evaluate and understand the insulator material particularly the fillers or additives used so that an informed decision can be made when selecting RTV silicone rubber coating as an insulator material.

Evaluating effect of insulator profile revealed that Structure-2, with all RTV silicone rubber post insulators, recorded lower magnitudes of leakage current for most parts of the year compared to Structure-3 (two long rods and one post HTV silicone rubber insulator). The results from measurements on full scale woodpole structures show a 56% decrease in leakage current. Both structures' leakage currents were affected by a dry spell with very heavy pollution where hydrophobicity of the insulators is suspected to have been compromised by accumulation of very heavy pollution and spikey leakage current levels were recorded. Once the material has recovered, the effect of insulator profile favours application of insulators with wide shed diameter and large inter-shed spacing for improved leakage current performance of the structure. The results concur with by El-Hag et al. in [17] and differ from the outcomes of the measurements on reduced scale woodpole structure. It is suspected that the results obtained from measurements on reduced scale woodpole structures when investigating the effect of insulator profile were essentially affected by the 4% increase in humidity which resulted in sporadic tracking activity for the structure case with only HTV silicone rubber post insulators and possibly lead to high leakage current compared to the case with HTV long rod insulators. Only the outcomes from the literature study and measurements on full scale woodpole structures are therefore advocated.

Visual inspections demonstrated that for wood cross-arms the use of capped insulators to provide a conductive path for leakage current to flow from the insulator surface though the bonding wire in order to eliminate woodpole cross-arm pole-top fires is effective. No signs of carbon, external tracking or burning were observed on the cross-arm of Structure-1 and Structure-2. The correct bonding application also played a significant role since there were no signs of tracking between the insulator spindle metal and woodpole cross-arm interfaces and also between the vertical woodpole and the brace strap metal or the steel frame. Therefore leakage current performance of a structure is improved when the insulators are applied in conjunction with correct bonding practice. Furthermore it was observed from the inspections that Structure-1 with all vertical porcelain insulators suffered deeper tracking at the insulation coordination gap than on Structure-2 and Structure-4 where short and shallow tracking marks with smouldering around the bandit strap were observed.

4.7 Summary

Section 4 presented simulated field experimental results on full scale woodpole structures exposed to natural coastal pollution. Results of the logged leakage currents for a year were discussed. Improved leakage current performance was observed on structures with insulators that are made of silicone rubber insulator material, have wide shed diameter insulator profile and for the structure with two horizontally orientated insulators.

5 REVIEW OF OUTCOMES AND ANSWERS TO RESEARCH QUESTIONS

5.1 Literature Survey

To evaluate the effect of insulator application on the leakage current performance of woodpole distribution line structures, a literature survey was conducted to determine the current knowledge regarding pole-top fires and individual insulator leakage current performance and to obtain direction and expectations for the proposed laboratory tests. The survey showed that individually tested insulators exhibit different leakage current performance depending on choice of insulator material or insulator profile. Traditionally, glazed porcelain insulators are used and also for improved environmental performance under polluted conditions polymer insulators are used. Although silicone rubber material may show better leakage current performance over porcelain material, additives and fillers used in silicone affect the performance and degradation by environmental factors.

A review of mitigation of pole-top fires indicated that as long as there is wood in the leakage current path the structure remains at risk of burning. The risk can be reduced by tightly bonding the unenergised hardware and earthing it through a 500 mm gap. The risk can be eliminated by replacing the gap with a continuous earth downwire or replacing the entire woodpole structure with a non-combustible material such as concrete or steel. However, other aspects of line performance, such as lightning performance, bird safety and cost, also need to be considered when deciding on the design of an overhead power line structure (these are out of the scope of this study).

5.2 Test Results

Reduced scale and full scale tests were performed to obtain leakage current magnitudes for comparison of the effect of insulator orientation, insulator material and insulator profile. Leakage current was measured along the earth downwire (below the insulation coordination gap) instead of being measured through the insulator pollution layer at the base of the phase insulators (i.e. measuring the leakage current performance of individual insulators) so as to measure leakage current performance of a complete three phase MV distribution woodpole structure with phase insulators, partial bonding and related hardware. The results are summarised in Table 5.1 and Table 5.2.

Table 5.1: Summary of laboratory measurements on reduced scale woodpole structure. (Scaled down structure with wood cross-arm and partially bonded through an insulation coordination gap)

Evaluated case with insulator details	Leakage current results
Case 1 • Porcelain posts • Short & wide • All vertical	Effect of insulator orientation High leakage current magnitude compared to case with 2x horizontal porcelain insulators. Effect of insulator material High leakage current magnitude compared to case with HTV silicone rubber insulators. Voltage at insulation coordination gap Neutral voltage shift observed.
Case 2 • Porcelain posts • Short & wide • 2x horizontal, 1x vertical	Effect of insulator orientation Low leakage current magnitude compared to Case 1. An average difference of ≈ 24% in leakage current magnitude with pollution of 10 kg/m^3 salinity. Voltage at insulation coordination gap Neutral voltage shift observed.
Case 3 • HTV silicone rubber posts • Short & wide • All vertical	Effect of insulator material Low leakage current magnitude compared to Case 1. An average of ≈ 62% leakage current magnitude difference was observed. The leakage current magnitude difference is great for a higher pollution salinity of 112 kg/m^3 compared to pollution of low salinity at 40 kg/m^3. Effect of insulator profile High leakage current magnitude compared to Case 4 for weather conditions with humidity approximately 80% or above. Voltage at insulation coordination gap Neutral voltage shift observed.
Case 4 • HTV silicone rubber • 2x thin & long (long rods), 1x short & wide (post) • All vertical	Effect of insulator profile Low leakage current magnitude compared to Case 3. For humidity levels below 75%. Voltage at insulation coordination gap Neutral voltage shift observed.

Table 5.2: Summary of measurements on full scale woodpole structures

Evaluated structure description and insulator details	Leakage current results	Visual observations
Structure-1 • Wood cross-arm • Partially bonded & earthed through gap • Porcelain insulators short & wide • All insulators vertical	Effect of insulator orientation High leakage current magnitude compared to Structure-4 under heavy pollution. Similar leakage current level observed for both structures for light pollution conditions during rainy season. Effect of insulator material High leakage current magnitude most of the year particularly for very heavy pollution conditions during a dry season when compared to Structure-2 and Structure-3.	• No tracking on the cross-arm. • Severe tracking in the insulation coordination gap. • Highest risk of burning.
Structure-2 • Wood cross-arm. • Partially bonded & earthed through gap. • RTV silicone rubber coating. • Short & wide. • All insulators vertical.	Effect of insulator material Low leakage current magnitude most of the season except after a dry season with very heavy pollution, when compared to Structure-1. Effect of insulator profile Low leakage current magnitude for most of the year except for after a dry season with very heavy pollution, when compared to Structure-3. Approximately up to 56% decrease in leakage current can be realised.	• No tracking on the cross-arm. • Several short tracking marks & smouldering around the bottom bandit strip inside the insulation coordination gap. • Moderate risk of tracking further.
Structure-3 • Steel cross-arm • Solidly earthed by continuous earth downwire. • HTV silicone rubber insulators, 2x thin & long (long rods), 1x short & wide (post). • All insulators vertical.	Effect of insulator material Low leakage current magnitude for nearly the entire year, when compared to Structure-1. Effect of insulator profile High leakage current magnitude compared to Structure-2.	• No tracking on the cross-arm. • No significant risk of burning.
Structure-4 • Steel A-frame cross-arm. • Partially earthed through gap. • Porcelain insulators, short & wide, 2x horizontal, 1x vertical.	Effect of insulator orientation Low leakage current magnitude compared to Structure-1. However comparable leakage current level to Structure-1 for light pollution conditions during rainy season.	• No tracking on the cross-arm. •Tracking at the top bandit strap and at the bottom earth downwire inside the gap. • Low risk of tracking further.

5.3 Summary of Consolidated Results

Integrating all outcomes from the literature review, reduced scale tests and full scale tests, the research questions may be answered as follows:

1. What is the effect of insulator orientation on the leakage current (along the earth downwire) of a MV woodpole distribution structure?

    - Mounting the two outer phase insulators in a horizontal position reduces the leakage current magnitude of a woodpole structure noticeably for heavy pollution during a dry spell, but not significantly for light pollution during a rainy season. The effect of insulator orientation can impact leakage current performance of a woodpole structure such that leakage current magnitude flowing on a structure with all insulators vertically mounted may be reduced by approximately 24% by changing the outer insulators to be mounted in a horizontal position.

2. What is the effect of insulator material on the leakage current (along the earth downwire) of a MV woodpole distribution structure?

    - Using silicone rubber insulators on a woodpole structure results in leakage current magnitudes that are significantly less than those flowing on the same structure using porcelain insulators. A structure with RTV silicone rubber coated insulators mounted vertically has a reduced leakage current compared to the same structure with porcelain insulators provided the RTV silicone rubber coating hydrophobicity is still retained. It is to be noted that the hydrophobicity of RTV silicone rubber coating deteriorates over time (at a rate dependent on the fillings or additives used) and reapplication will be necessary. Taking cognizance of the extensive length of Eskom's distribution network likely to experience pole-top fires, the work effort required to apply and reapply the silicone rubber may be cumbersome and expensive over the lifetime of the network. A structure using HTV silicone rubber insulators that are all positioned vertically will also result in leakage current magnitudes that are approximately 62% less when compared to the same structure using porcelain insulators. The advantage of using HTV silicone rubber insulators instead of applying RTV silicone rubber coatings on porcelain insulators is that to replace HTV silicone rubber insulators requires less effort compared to reapplying porcelain insulators with a RTV silicone rubber coating.

3. What is the effect of insulator profile on the leakage current (along the earth downwire) of a MV woodpole distribution structure?

    - A structure with RTV silicone rubber post insulators will have less leakage current than with HTV silicone rubber long rod insulators. The former structure utilising post insulators with a profile comprising a broad shed diameter (diameter range of 115-180 mm) and wide shed-to-shed spacing, can have approximately 56% less leakage current than the latter structure.

The answer to the research question "can the magnitude of leakage current be reduced from improved application of insulator orientation, insulator material and insulator profile on a woodpole distribution structure" is yes - by using a delta structure configuration with two horizontally-mounted porcelain insulators or by using a horizontal structure configuration with HTV silicone rubber insulators comprising a wide and short profile such as post insulators.

5.4 Suggested Insulator Application Choices for Minimised Risk of Pole-Top Fires

In terms of minimising the risk of pole-top fires occurring by using only insulator selection and application, the following suggestions are made. They are to be applied together with a suitable bonding method:

1. When porcelain insulators are used on a woodpole distribution structure, it is better to mount the outer phase insulators in a horizontal position so that solid particle pollution may fall through and not settle on top of the sheds and that rain or wind may naturally clean them effectively. This will result in leakage current magnitudes that are lower compared to the structure with insulators that have a vertical arrangement.

2. When HTV silicone rubber insulators are used due to their hydrophobicity and better leakage current performance compared to porcelain insulators, only post insulators with alternating sheds should be used because such a profile contributes to better leakage current performance compared to long rod insulators with a long and slim profile.

3. In addition, when RTV silicone rubber coated insulators are used for reasons stated regarding HTV silicone rubber insulators, provision for reapplication should be made because of the fact that their hydrophobicity will be degraded by environmental elements and reapplication will be required after a few years.

The most attractive solution (from a leakage current point of view) is therefore a fully bonded and earthed structure that uses insulators with HTV silicone rubber insulator material, having a post profile and alternating sheds.

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary and Conclusions

The following are the main conclusions to be drawn from this work:

- A study to evaluate the effect of insulator selection and application on the leakage current performance of medium voltage woodpole overhead distribution line structures was presented. This was achieved by considering the effect of insulator orientation, insulator material and profile.

- Findings from reduced scale laboratory tests were presented. To build confidence and confirm the laboratory outcomes year long full scale leakage current tests were also performed.

- Of the three items considered, structure leakage current performance was found to be most affected by insulator material, because a large difference in leakage current magnitude was witnessed between materials and reasonably consistently low leakage current levels were observed for RTV silicone rubber coated porcelain insulators for most of the seasons. The risk of pole-top fires occurring on woodpole distribution structures using porcelain insulators can be reduced by using RTV silicone rubber coated porcelain insulators or by replacing the porcelain insulators with HTV silicone rubber insulators. The choice of RTV silicone rubber coated insulators has shortcomings such as loss of hydrophobicity due to degradation by environmental elements and reapplication needed after a few years. The extensive length of the distribution network is also a limiting factor. The use of HTV silicone rubber insulators is better for retrofit because replacing the insulators is not labour intensive and the likelihood of compromised quality of work would be less compared to spray coating porcelain insulators.

- The effect of the profile of silicone rubber insulators was found to be favourable towards designs with wide shed diameters, such as post insulators, i.e. “short and wide” insulators exhibited lower leakage current than “long and thin” insulators of the same or similar creepage distance.

- For porcelain post insulators, orientation of the outer phase insulators has minimal effect on the level of leakage current flowing on a woodpole structure under light pollution. However, under heavy pollution, e.g. during a dry season, improved leakage current performance on a woodpole structure can be achieved through the application of horizontally-mounted outer phase insulators.

- In conclusion a fully bonded and earthed structure with horizontal configuration (all insulators mounted vertical) will offer the best leakage current performance when post-type HTV silicone rubber insulators with alternating sheds are used.

6.2 Recommendations for Future Work

Based on the above conclusions the following is recommended:

1. A comparison of the structure's leakage current and the insulation coordination gap's voltage presented showed that there is an increase in the neutral voltage shift for certain conditions. This should be further explored to better understand the effect of this voltage on the leakage current on a woodpole structure and on the risk of pole-top fires occurring.

2. A software model for a typical woodpole distribution structure earthed through a (500 mm) insulation coordination gap should be developed so as to simulate the effect of different bonding arrangements, wood impedance and insulator application on the leakage current performance of such structures.

3. For HTV silicone rubber insulators or RTV silicone rubber coated porcelain insulators, the effect of insulator material should be explored further to compare and establish which fillers or additives are most suitable for making the insulator material more resilient for longer life in service.

REFERENCES

[1] Eskom, “Distribution Standard Part 4: Medium voltage reticulation Section 1: MV Overhead Reticulation”, Eskom internal document, February 1999.

[2] P.M. Ross, “Burning of wood structures by leakage current”, AIEE Transactions, Vol. 66, pp 279- 287, 1947.

[3] K.V Thejane, M.D. Ntshani, H.J. Geldenhuys, J.M, Van Coller, A.A Beutel, W. Vosloo, T.D Mvayo, R. Watson, A. Khatri, “Effect of insulator application on the leakage current performance of woodpole distribution line structures”, ISH 2013, August 2013.

[4] K. V. Thejane, A. A. Beutel, M. D. Ntshani, H. J. Geldenhuys, A. C. Britten, W. Vosloo, T. D. Mvayo, R. Watson, R. Swinny, C. R. Evert, A. Khatri, “Pole Top Fires: Review of work to Date and case for Further Research”, IEEE PES Power Africa 2012 Conference and exposition, pp 7B-1, July 2012.

[5] A. K. Persadh: “A study of pole top fires on 22 kV wood pole power lines in KwaZulu Natal”, Dissertation for Master of Science in Electrical Engineering, University of KwaZulu-Natal, October 2007.

[6] M. Darveniza, “Electrical properties of wood and line design”, University of Queensland Press, pp. 115-128, 1980.

[7] A. Beutel, H. Geldenhuys, B. McLaren, M. Ntshani, K. Thejane, A. Khatri, “Pole-top fires risk assessment: A South African perspective”, CIRED,22nd International Conference on Electricity Distribution, Stockholm, June 2013.

[8] K. L. Wong, M. F. Rahmat, “Feasibility study of leakage current shunting method based on the ladder network model”, IEEE Transactions on Power Delivery, Vol. 25, Issue 2, 2010, pp. 1133 – 1137.

[9] K. L. Wong, M. F. Rahmat, “Feasibility study of leakage current shunting method on wooden pole”, Paper C-56, International Symposium on High Voltage Engineering (ISH 2009), August 2009.

[10] SANS 60815 Part 1 – Part 3: 2009, Edition 1 “Selection and dimensioning of high-voltage insulators intended for use in polluted conditions”.

[11] W. L. Vosloo, R.E. Macey, C. de Tourreil: “The practical guide to outdoor high voltage insulators”, Eskom Power Series, Vol. 3, pp. 24-27, pp. 54-70, September 2006.

[12] W. L. Vosloo: “A comparison of the performance of high-voltage insulator materials in a severely polluted coastal environment”, Dissertation for Doctor of Philosophy in Engineering Science, University of Stellenbosch, March 2002.

[13] K. L. Wong, S. Pathak, X. Yu, "Aging effect on leakage current flow in wooden poles" IEEE Transactions on Dielectrics and Electrical Insulation, vol. 16, no. 1, February 2009.

[14] R. Filter, "The influence of wood pole preservatives on wood fire and electrical safety", IEEE Transaction on Power Apparatus and Systems, vol. PAS-103, no. 10, October 1984.

[15] J. B. Wareing, H. Blad, P. Kumar, "Upgrade distribution assets in Oman: Extreme weather and environmental conditions upgrading and uprating of transmission and distribution assets", CIGRE Auckland Symposium, 2013.

[16] CIGRE Taskforce 33.04.01, "Polluted insulators: A review of current knowledge", CIGRE brochure N°158-2000.

[17] A. H. El-Hag, S. H. Jayaram and E. A. Cherney "Effect of Insulator Profile on Aging Performance of Silicone Rubber Insulators in Salt-Fog" IEEE Transactions on Dielectrics and Electrical Insulation Vol. 14, No. 2, pg 352-359, April 2007.

[18] K. L. Chrzan., W. L. Vosloo, J. P. Holtzhausen, "Leakage current on porcelain and silicone insulators under sea or light industrial pollution", IEEE Transaction on power delivery, Vol. 26, No. 3, July 2011.

[19] T. Sorqvist, "Long-term field experience with RTV coated porcelain insulators", 2000 IEEE International Symposium on Electrical Insulation, Anaheim, USA, April 2000.

[20] K. Weiczorek, J. Fleszynski, W. Bretuj, "Effect of shape of insulator housings and positions of composite insulators on ageing resistance under high voltage and precipitation", IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 19, No. 3. June 2012.

[21] D. Pylarinos, K. Siderakis, E. Pyrgioti, "Measuring and analysing leakage current for outdoor insulators and specimens", Advanced Study Center Co. Ltd, 2011.

[22] S. H. Kim, E. A. Cherney, "Effect of filter level in RTV silicone rubber coatings used in HV insulators", IEE Transaction on Electric Insulators, Vol. 27, No.6, December 1992.

[23] M. F. Rahmat, K. L. Wong, "Thermographic study of stainless steel cross-arm on overhead distribution system", 2009 Australasian Universities Power Engineering Conference (AUPEC), 2009, pp. 1-6

[24] W. L. Vosloo, R. Swinny, T. Mvayo, J. P. Holtzhausen, "Koeberg Insulator Pollution Test Station (KIPTS)-from research facility to an in-house insulator product ageing test standard", INMR Conference, Shanghai, 2001.

[25] C. Van Der Merwe, W. L.Vosloo, K. Holtzhausen, “Insulation coordination short course”, Centre for Electrical and Electronic Engineering, University of Stellenbosch, pp. 703-704, 2008.

[26] K. V. Thejane, J. M. Van Coller, M. D. Ntshani, A. A. Beutel, “Leakage current performance evaluation of woodpole distribution line structures”, ISH 2015, August 2015.

[27] A. C. Britten, “Practical insulation co-ordination of woodpole Distribution lines in high-lightning areas” IEEE Africon, Swaziland, 1994.

[28] A. De La O, R. S. Gorur, J. Chang, “AC clean fog tests on non-ceramic insulating materials and a comparison with porcelain”, IEEE transaction on Power Delivery, Vol. 9, No. 4, October 1994.

APPENDIX A: DEFINITION OF INSULATOR TERMS AND PARAMETERS USED IN THIS REPORT

Note: Detailed explanations are found in [10] and [11]. Figure A.1 illustrates some of the insulators parameters.

- Ceramic insulators can either be made of toughened glass or porcelain. Porcelain is made from clay where after processing it is glazed to have a smooth finish. Porcelain is prone to breaking or chipping compared with glass [11].
- Polymer insulators can either be composite or cast. Polymer composite insulators comprise a fibreglass core that can either be housed within High Temperature Vulcanised (HTV) silicone rubber or Ethylene Propylene Diene Monomer (EPDM). Room temperature vulcanized silicone rubber is available for application as a coating on porcelain insulators. Silicone rubber has the best ability to repel water and limit leakage current compared to porcelain [11].
- Post type insulators are wide and cylindrically shaped insulators typically designed to be firmly mounted on a structure for support of a conductor [11].
- Long rod type insulators are typically thin and long compared to post type insulators and are used for suspension of a conductor [11].
- Pin type insulators are usually glass or porcelain. They consist of a disc with a pin through it that can be connected to form a long insulator string [11].
- Metal end fitting are typically at the ends of an insulator. The one end is used to attach the conductor and the other end is attached to the structure.
- Sheds are designed to increase the creepage distance
- The shed to shed spacing is the distance between sheds [10].
- The creepage distance is the total insulator length from the metal end fitting along the shed surface [10].
- The specific creepage distance is the creepage distance divided by the line-to-line r.m.s. voltage of a three phase system [10].

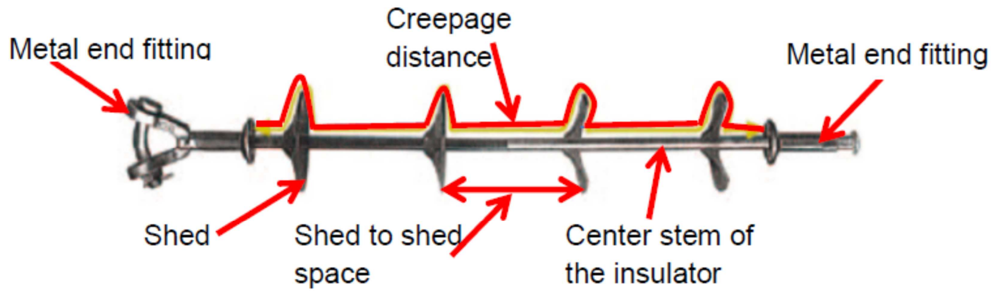


Figure A.1: "Insulator parameters illustration" [11 p.9]

APPENDIX B: DATA SHEETS OF INSULATORS USED ON THE STRUCTURES DURING MEASUREMENTS

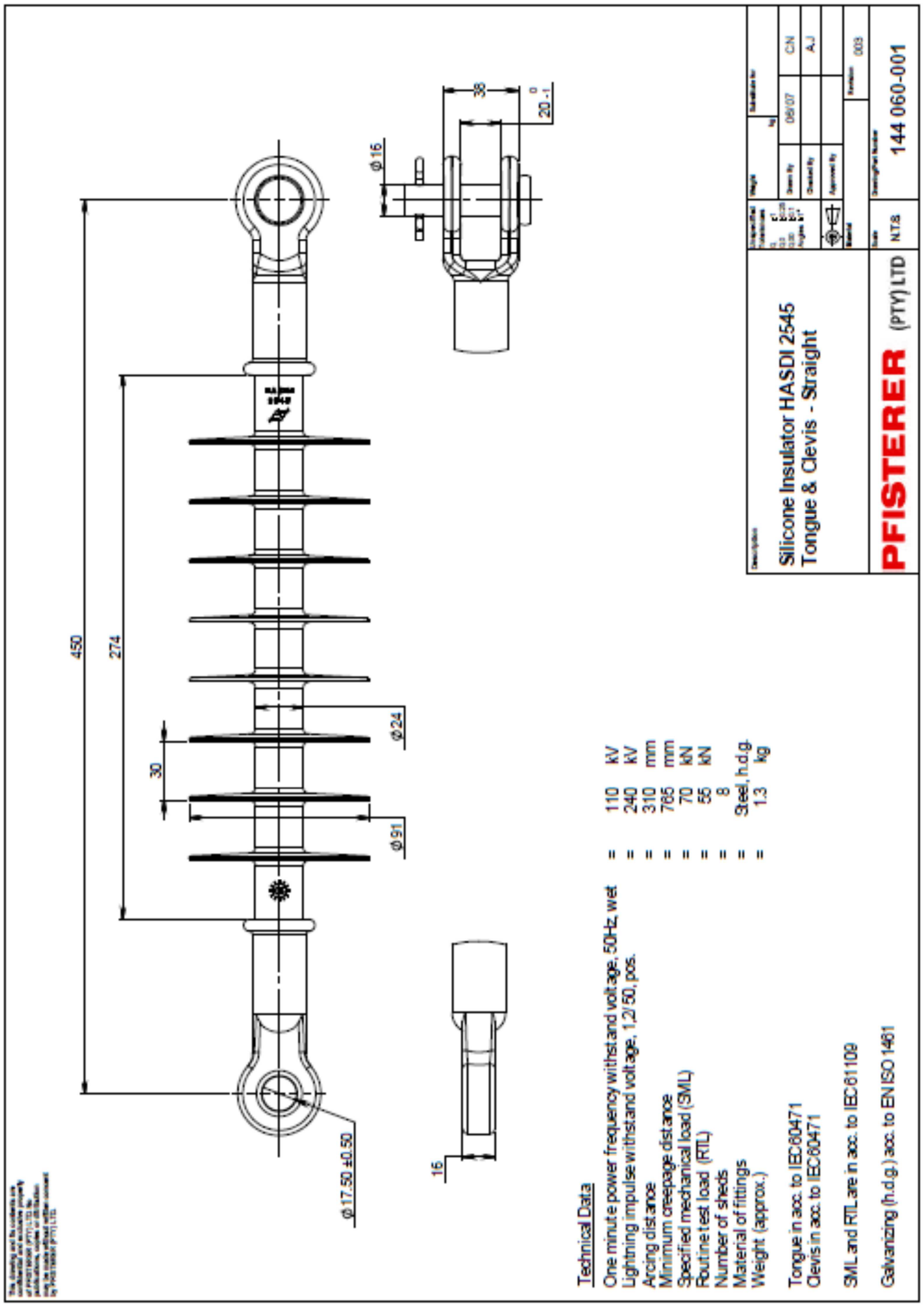


Figure B.1: HTV silicone rubber long rod insulator specification

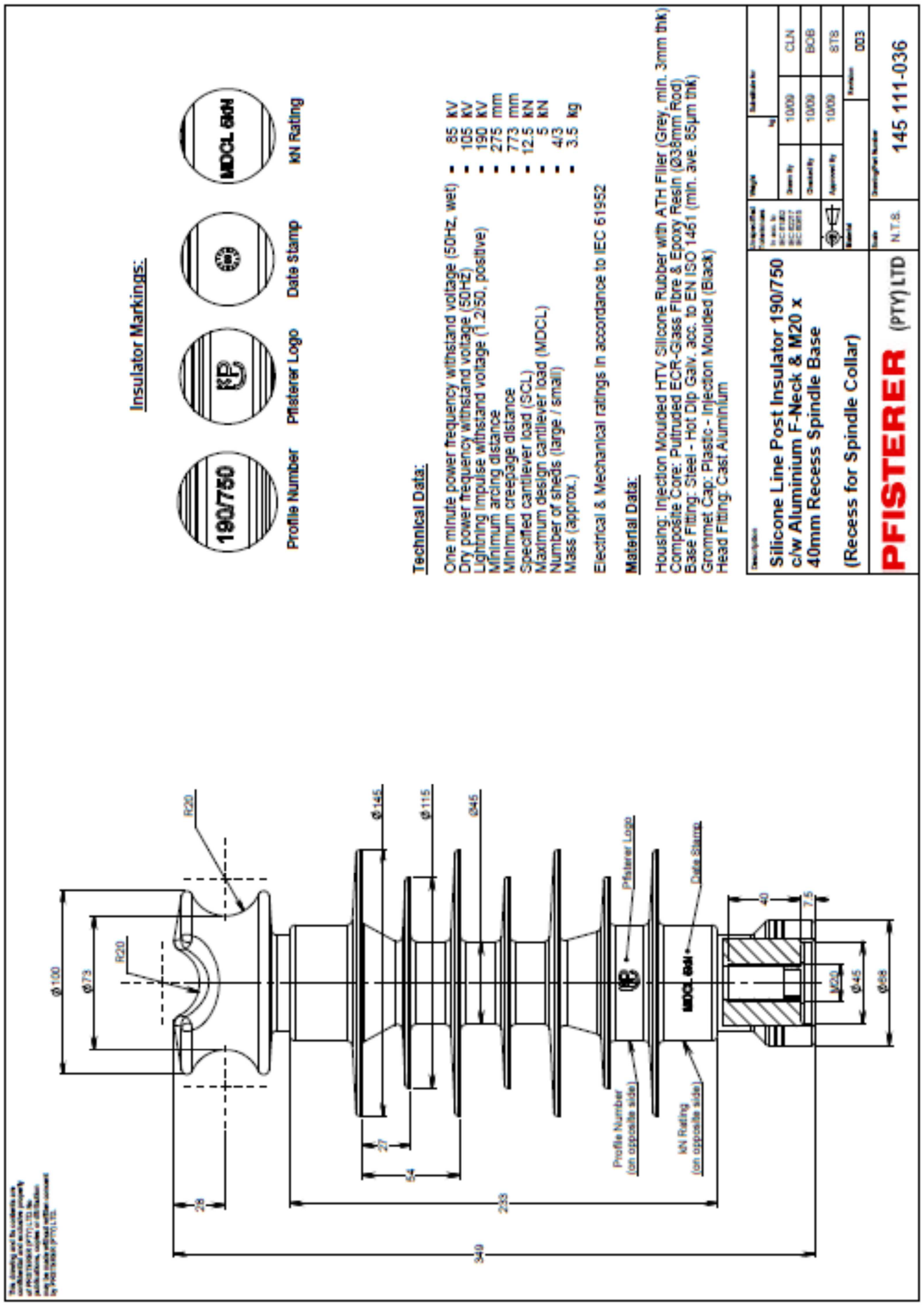
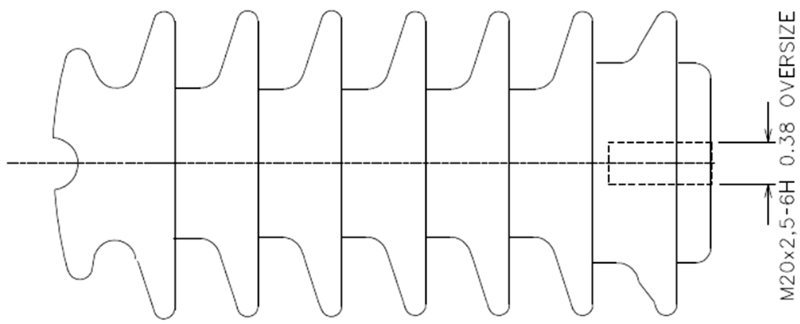


Figure B.2: HTV silicone rubber post insulator specification

TYPICAL



NOTE :

* 4kN POST INSULATORS ARE TO BE USED ON ALL LINES UP TO OAK/HARE CONDUCTORS.
* 10kN POST INSULATORS TO BE USED WITH ALL CONDUCTORS AT ROAD CROSSINGS AND ON LINES WITH CONDUCTORS LARGER THAN OAK/HARE UP TO KINGBIRD CONDUCTOR.

ITEM	:-	INSUL,POST 33kV
MATERIAL SPECIFICATION	:-	PORCELAIN, CYCLO ALAPHATIC, COMPOSITE
FAILING LOAD (kN)	:-	4kN AND 10kN MINIMUM
CREEPAGE DISTANCE (mm)	:-	720mm (20mm/kV) & 1116mm (31mm/kV)
STANDARD SPECIFICATION	:-	F-NECK
ESKOM SPECIFICATION	:-	DSP_34-1677
LAP MATERIAL GROUP	:-	LINE POST INSULATORS
TEST & CERTIFICATION REQUIREMENTS	:-	TESTS AS PER DSP_34-1677

INSPECTION	Yes	No	ESKOM RELEASE NOTE	Yes	No

IDENTIFICATION:- INDELIBLE MANUFACTURES TRADEMARK & PART No. ON ALL ITEMS

REV	REVISION DESCRIPTION	BY	CHKD	AUTH	DATE	REF. DWGS
10	INSUL,CAPPED POST 4N AND 10N SPINDLE CHANGED	P.A.T.	B. HILL	B. HILL	20.05.2014	
9	TOTAL CREEPAGE ADDED IN ADDITION TO SPECIFIC CREEPAGE DISTANCE & SPEC REFERENCE UPDATED	JJJ	J J JORDAAN	J J JORDAAN	07.08.2009	
8	SHORT DESCRIPTIONS CORRECTED	N.M.	D. RAMJASS	D. RAMJASS	21.03.2009	

AUTH:	P. CROWDY	DATE:	06.10.1997	SCALE: NTS	Eskom	SAP No:		
CHKD:	D. PILLAY	DATE:	06.10.1997	CAD REF: SERIES 3000		SET	SHEET	REV
DRAWN:	P.A. VERMAAK	DATE:	04.10.1997	FILE No: 3189	D-DT-3189	3	1	10

Figure B.3: Porcelain post insulator specification

SPEC SHEET

SAP MATERIAL No.:	0216691
SHORT DESCRIPTION:	INSUL,L/POST COMP 33kV 10kN HVH D3189

TECH. DESCRIPTION:

COMPOSILE LINE POST INSULATOR * FOR HEAVY AND VERY HEAVY POLLUTION AREAS *
RATED VOLTAGE: 33kV * MINIMUM REQUIRED TOTAL CREEPAGE DISTANCE: 1116mm *
SPECIFIC CREEPAGE: 31mm/kV @ 36kV Um * CANTILEVER STRENGTH: 10kN *
LIGHTNING IMPULSE WITHSTAND: 170kV * RATED 50Hz WET WITHSTAND: 50kV *
F-NECK * INSERT M20x2.5-6H (0.38mm OVERSIZE) * 55mm THREAD DEPTH *
SPINDLE D-DT-3050 * FOR USE UP TO OAK/HARE AND CU CONDUCTOR *
LINE POST INSULATORS TO BE APPROVED BY INSULATOR WORK GROUP *
ESKOM DRAWING No. D-DT-3189 *

SAP MATERIAL No.:	0216396
SHORT DESCRIPTION:	INSUL,CAPPED POST 33kV 4kN HVH D3189

TECH. DESCRIPTION:

LINE POST INSULATOR (CAPPED) * FOR HEAVY AND VERY HEAVY POLLUTION AREAS *
RATED VOLTAGE: 33kV * MINIMUM REQUIRED TOTAL CREEPAGE DISTANCE: 1116mm *
SPECIFIC CREEPAGE: 31mm/kV @ 36kV Um* CANTILEVER STRENGTH: 4kN *
LIGHTNING IMPULSE WITHSTAND: 200kV * RATED 50Hz WET WITHSTAND: 70kV *
F-NECK * CAP M20x2.5-6H (0.38mm OVERSIZE)* 55mm THREAD DEPTH *
SPINDLE D-DT-3050*
FOR USE UP TO OAK/HARE CONDUCTOR *
LINE POST INSULATORS TO BE APPROVED BY INSULATOR WORK GROUP
INSULATOR TO BE BROWN IN COLOUR FOR 4kN POST INSULATORS *
ESKOM DRAWING No. D-DT-3189 *

SAP MATERIAL No.:	0216397
SHORT DESCRIPTION:	INSUL,CAPPED POST 33kV 10kN HVH D3189

TECH. DESCRIPTION:

LINE POST INSULATOR (CAPPED) * FOR HEAVY AND VERY HEAVY POLLUTION AREAS *
RATED VOLTAGE: 33kV * MINIMUM REQUIRED TOTAL CREEPAGE DISTANCE: 1116mm *
SPECIFIC CREEPAGE: 31mm/kV @ 36kV Um * CANTILEVER STRENGTH: 10kN *
LIGHTNING IMPULSE WITHSTAND: 200kV * RATED 50Hz WET WITHSTAND: 70kV *
F-NECK * CAP M20x2.5-6H (0.38mm OVERSIZE)* 55mm THREAD DEPTH *
SPINDLE D-DT-3050*
FOR USE UP TO OAK/HARE CONDUCTOR *
LINE POST INSULATORS TO BE APPROVED BY INSULATOR WORK GROUP
INSULATOR TO BE GREY IN COLOUR FOR 10kN POST INSULATORS *
ESKOM DRAWING No. D-DT-3189 *

REV	REVISION DESCRIPTION	BY	CHKD	AUTH	DATE	REF. DWGS
10	INSUL,CAPPED POST 4N AND 10N SPINDLE CHANGED	P.A.T.	B. HILL	B. HILL	20.05.2014	
9	TOTAL CREEPAGE ADDED IN ADDITION TO SPECIFIC CREEPAGE DISTANCE & SPEC REFERENCE UPDATED	JJJ	J J JORDAAN	J J JORDAAN	07.08.2009	
8	SHORT DESCRIPTIONS CORRECTED	N.M.	D. RAMJASS	D. RAMJASS	21.03.2009	

AUTH:	P. CROWDY	DATE:	06.10.1997	SCALE: NTS	SAP No: 0216691 0216396 0216397
CHKD:	D. PILLAY	DATE:	06.10.1997	CAD REF: SERIES 3000	Eskom
DRAWN:	P.A. VERMAAK	DATE:	04.10.1997	FILE No: 3189	D-DT-3189 — SET 3, SHEET 3, REV 10

APPENDIX C: LABORATORY PROCEDURE FOR MEASUREMENTS CONDUCTED AT ESKOM'S CORONA CAGE

PROCEDURE FOR MEASUREMENT OF DOWNWIRE INSULATOR (OR BASIC INSULATION LEVEL - BIL) VOLTAGE AND DOWNWIRE CURRENT WAVEFORMS ON ENERGISED 11 kV (PHASE-TO-EARTH) WOODPOLE STRUCTURES FOR RESEARCH PURPOSES AT THE CORONA CAGE

Compiled: Mikhuva Ntshani and Keneilwe Thejane

Date: 02 January 2014

1. Introduction

The objectives of the measurements are to:

- Measure the magnitude and waveform of the voltage across the BIL gap or across the downwire insulator and simultaneously measure the downwire current:
    - Determine the relationship between the measured voltage and the downwire current.
- Measure the approximate impedance of the woodpole at the BIL gap and the downwire insulators using the measured waveforms. Also determine the approximate ratio of current flowing along the downwire insulator and current flowing along the downwire insulator.
    - Deduce whether the downwire insulator can effectively divert leakage current from flowing along the surface or inside the interior of the wood.
    - Record visible state of the test structure.

2. Measurement set-up and methodology

The measurement of current flowing down the woodpole, along the downwire insulator and the voltage waveforms will be measured simultaneously (if possible and if safe to do so). Alternatively, the test may be broken down into two parts, i.e. measurement of the downwire insulator voltage (or BIL gap) and of the downwire current simultaneously; and simultaneous measurement of current flowing on the woodpole and across the downwire insulator (or bonding wire).

Fig 1 depicts measurement set-up for the BIL gap voltage and current flowing down the woodpole.

A 1000: 1 Tektronix high voltage (HV) probe is used to measure the voltage between the point above the downwire insulator (or BIL gap) and earth similar to previous tests at KIPTS.

CSLW Series miniature wired open-loop current sensors with power supply circuit were chosen for measuring current flowing along the woodpole and along the downwire insulator. This sensor was chosen due to the fact that it offers galvanic isolation (approximately 500 V), provides low sensitivity (40 mA), low cost and was available at the time of testing. Although the galvanic isolation of the sensor is significantly low compared to other sensors (e.g. 6.6 kV for the sensor used at KIPTS), the isolation was considered to be adequate. This is because the sensor will be connected between the downwire insulator or BIL gap and earth. The isolation was considered adequate provided the sensor is used with a reliable earthing system. Two of these sensors will be used to measure current flowing down the woodpole and along the downwire insulator simultaneously.

The outputs of the current sensor(s) and the HV probe are connected to the oscilloscope. The oscilloscope used is powered by a battery. It has a common earth point that ties the reference (outer) connections of the measurement channels to it. This scope's earth point is connected to the station earth and therefore all measurements are referenced to the same point.

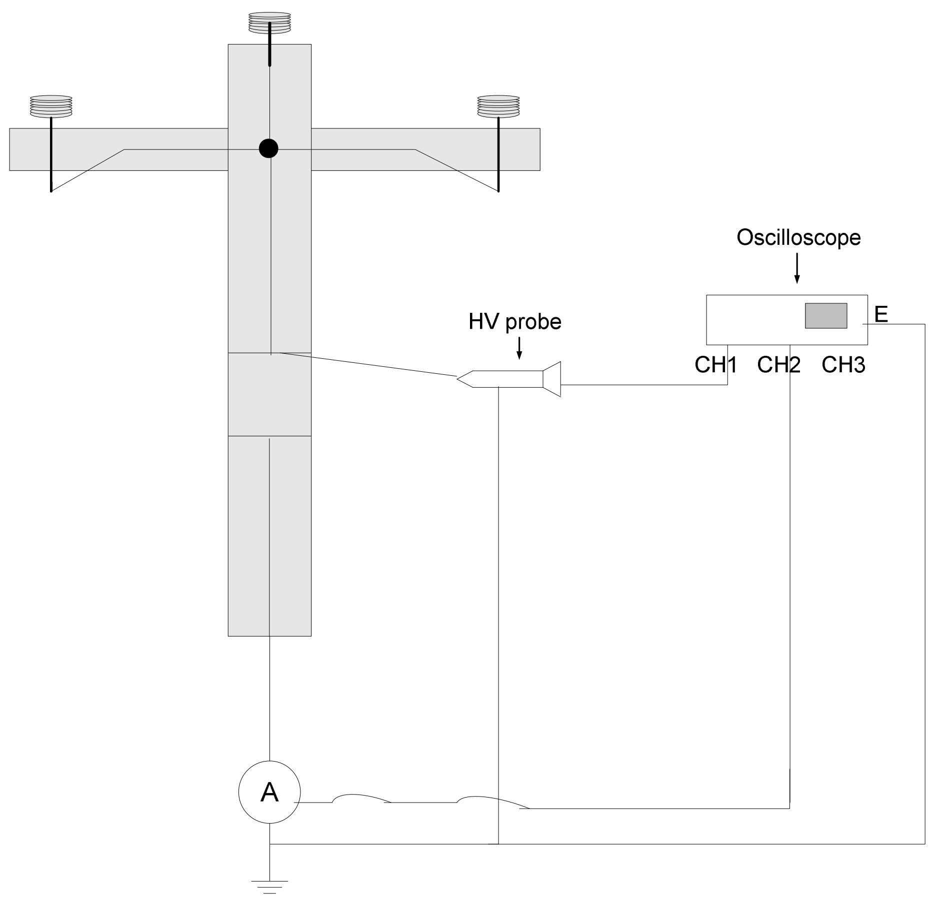


Figure C.1: Structure leakage current measurement method

2.1 Measurement procedure

2.1.1 Before energisation

The following will be performed whilst the structures are unenergised:

- Before the project is started, a written risk assessment will be conducted. The risk assessment will identify all possible hazards and danger that may be encountered during the testing. Such hazards include the high voltage power, tripping hazards, etc. For subsequent days' work, a verbal assessment must be done prior to starting work, identifying any changes from the original assessment that may cause an impact on the work.
- The life saving rules will be observed.
    - Ensure there is a permit to perform the work and that the workers register is signed and all potential risks are identified and recorded and appropriately mitigated against.
    - Wear appropriated protective clothing including safety boots and appropriately rated rubber gloves.
    - Check visually that the three phase supply socket plug is switched off and the three phase cable to the transformers is removed (isolated) from the socket plug.
- Visually confirm that the single earth point is in fact connected to the corona cage station earth (i.e. the central earth point is on the metallic transmission tower base at which point the station earth is connected).
- Visually confirm that all three high voltage phases of the independent three phase transformers are earthed to the central earth point.
    - Use an earth stick to discharge the line and the structure.
    - Test that the line and the transformers are dead using the voltage indicator probe.
- Test that the HV probes and channels of oscilloscope are working. This is accomplished by connecting the HV probe to the 220 V mains and measuring the voltage on all channels on the oscilloscope.
- If in working condition, the probe must be connected tightly to the bonding wire by using a line trap or similar.
- Test that the two current sensors are working. This is accomplished by using a 220 V supply and known resistors to give current in the mA range.

The measurements should be recorded with an oscilloscope and confirmed with calculations using Ohms' law.

- If in working condition, the current sensors must be connected as in Fig 1. The bonding wire is connected between the Primary In and Primary out terminals, with the Primary out connected to earth side. The outputs of the sensors is connected between the Output terminal and ground.
    - Crocodile clipped probes or similar to be used for connections between the sensor and oscilloscope.
- Ensure that the oscilloscope is connected correctly.
- Ensure that all connections are making adequate contact; the earth connections are particularly important.
- Pollute the insulators (all phase insulators and, in some cases, also the downwire insulator) with brown sugar solution or kaolin until tacky and then spray with a salt solution. The brown sugar solution or kaolin solution may be applied using a brush.
- Inspect the set-up to ensure that all the connections are tight and in accordance with Fig 1.
- The oscilloscope must be setup to appropriately measure/record the currents and voltage including triggering levels.
- Ensure that appropriate barricades are in place and that safe clearances are understood by all present.
- Ensure that a fire extinguisher is on-hand near the test object.
- One person must be designated to supervise safety. This person should not directly be involved in conducting the testing.

2.1.2 Energisation

The following process will be followed when energizing the structure:

- Remove all the earths from the high voltage side of each single phase transformer.
- Connect the low voltage side of the transformers to the supply (i.e. connect the three phase cable plug to the mains and ensure that it is secured). Check that the breaker near the cage (behind the control room) has not tripped.
    - Switch the beaker on if it has tripped.
- Switch on the socket plug of the three phase supply cable.

Ensure that all the phases are energized by using a proximity sensor or similar and phasing stick. Please ensure that minimum safety clearances discussed in section 2.1.3 are maintained at all times.

2.1.3 After energisation, during testing

After energisation, the following will be performed:

- The scope must be at least 1 m away from the base of the test structure. It must also be at least 2 m away from the pole-top bonding (above BIL gap/down wire insulator) and at least 2 m away from all points that are energised at 11 kV. No operation of the oscilloscope will be allowed during energized conditions as during a fault situation, there is a possibility of currents flowing on the surface of the interconnected cable leads, thereby connecting dangerous voltages to the scope itself. No person shall encroach closer to the test setup than the clearances specified above for the oscilloscope.

- No person shall come into contact with the test structure or perform any connections to the structure or measurement system.

- The tests will be performed as follows:

    - Trigger the oscilloscope; stop and store results on the floppy disc.

    - Take several measurements (10 sets each).

- Perform visual state of test structures.

- A person shall be standing next to the 3-phase main supply switch at all times during tests. This is to ensure that if a problem such as an electrical fault or fire occurs, the person will be able to immediately open and isolate the mains power supply.

2.1.4 De-energisation

De-energisation will be performed at the end of each set of measurements and also when the insulators need to be polluted or wetted or any modifications or any other work needs to be performed on any part of the test setup, whether the test structure, measuring equipment or anything else. The following process will be adhered to:

- Switch off the 3-phase power supply (i.e. Open the power circuit)

- Remove the plug (i.e. isolate the test line)

- Test that the transformers and the line are dead, (i.e. there is no voltage on the line). This is done by first using a voltage proximity sensor and then a high voltage probe. If voltage is detected on the circuit then an earth stick must be used to discharge the line and the structure.

- Apply the three separate portable earths to the transformer high voltage output.

- Re-test that the transformers and the line are dead, (i.e. there is no voltage on the line).

2.2 General safety considerations

- No persons shall be allowed to work at heights unless trained and certified to do so.

- No persons shall cross any barricade or enter into the corona cage live chamber area, unless authorised to do so.

- Work will only be done in clear fair weather conditions and not at night.

- At least three people will be required to perform the work (1 operating the mains supply and earthing, 1 conducting the tests measurements and 1 supervising safety during the tests).

- All injuries and near misses to be reported immediately to the Authorised person, or Responsible person or Transmission Solutions Manager.

- The high voltage proximity sensor and high voltage probe must be self-tested for correct operation prior to use.

- Given that the test line is relatively short, inductive and electro-static charging thereof is not expected. However, if charge is measured on the line, then an equipotential zone must be created in addition to the earthing as described above. In this case all conductive parts must be bonded together. Additionally a worksite earth must be applied around the test object and bonded to the other conductive parts.